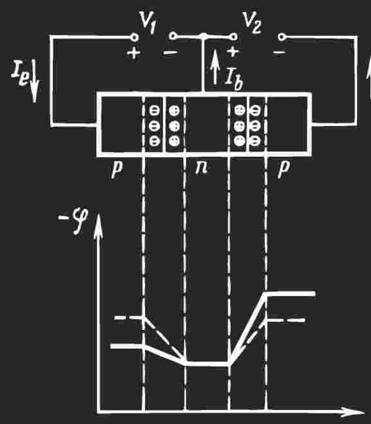
SEMICONDUCTORS
TESTING AND ADJUSTING

G. GREEN   A. SHOKALSKY



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ИЗДАТЕЛЬСТВО МИР

Г. И. ГРИН, А. А. ШОКАЛЬСКИЙ

НАСТРОЙКА И ИСПЫТАНИЕ ПОЛУПРОВОДНИКОВЫХ ПРИБОРОВ

ИЗДАТЕЛЬСТВО «ВЫСШАЯ ШКОЛА» МОСКВА

G. GREEN, A. SHOKALSKY

SEMICONDUCTORS

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The Russian Alphabet and Transliteration

А а	a	К к	k	Х х	kh
Б б	b	Л л	l	Ц ц	ts
В в	v	М м	m	Ч ч	ch
Г г	g	Н н	n	Ш ш	sh
Д д	d	О о	o	Щ щ	shch
Е е	e	П п	p	ъ	"
Ё ё	ë	Р р	r	ы	y
Ж ж	zh	С с	s	ь	'
З з	z	Т т	t	Э э	e
И и	i	У у	u	Ю ю	yu
Й й	y	Ф ф	f	Я я	ya

The Greek Alphabet

Α α	Alpha	Ι ι	Iota	Ρ ρ	Rho
Β β	Beta	Κ ϰ	Kappa	Σ σ	Sigma
Γ γ	Gamma	Λ λ	Lambda	Τ τ	Tau
Δ δ	Delta	Μ μ	Mu	Υ υ	Upsilon
Ε ε	Epsilon	Ν ν	Nu	Φ φ	Phi
Ζ ζ	Zeta	Ξ ξ	Xi	Χ χ	Chi
Η η	Eta	Ο ο	Omicron	Ψ ψ	Psi
Θ ϑ	Theta	Π π	Pi	Ω ω	Omega

На английском языке

List of Symbols

A	Voltage gain
α	Current amplification (gain) factor or current transfer ratio
B	Magnetic flux density
β	Current amplification (gain) factor for a common-emitter transistor
C	Capacitance
E	Electric field strength
ε	Electromotive force
f	Frequency
G	Power gain
H	Magnetic field strength, current gain
I	Electric current
I_b	Base current
I_c	Collector current
$I_{c.rev}$	Collector reverse or zero current with the emitter reverse-biased or the emitter circuit open
I_d	Dark current of a photoresistor
I_e	Emitter current
I_{ex}	Excitation current
I_{for}	Mean forward current averaged over a whole cycle
I_h	Holding current
I_{rec}	Rectified current
I_{rev}	Reverse current
I_s	Signal output current of a photoresistor
K_n	Noise factor
K_r	Ripple factor
K_s	Ripple smoothing factor
μ	Relative permeability
μ_o	Permeability of free space
n	Electron concentration or density
P	Power
p	Hole concentration or density

P_c	Collector power
P_R	Power rating
Q	Quality factor
R	Resistance
R_d	Differential resistance
θ	Operation angle
τ_{off}	Reverse-recovery or turn-off time
τ_{on}	Forward-recovery or turn-on time
V	Voltage or potential
V_b	Base voltage
V_{br}	Breakdown voltage
$V_{b.e}$	Base-emitter voltage
V_c	Collector voltage
$V_{c.b}$	Collector-base voltage
$V_{c.e}$	Collector-emitter voltage
V_e	Emitter voltage
V_{ex}	Excitation voltage
V_{for}	Mean forward voltage drop averaged over a whole cycle
V_h	Holding voltage
V_{rev}	Reverse voltage
$V_{r.m.s.}$	Root-mean-square (effective) voltage
V_{st}	Stabilizing voltage
X	Reactance
X_C	Capacitive reactance
Z	Impedance

Prefixes Used to Indicate Multiples or Submultiples

T	tera	10^{12}	m	milli	10^{-3}
G	giga	10^{9}	μ	micro	10^{-6}
M	mega	10^{6}	n	nano	10^{-9}
k	kilo	10^{3}	p	pico	10^{-12}
c	centi	10^{-2}			

Contents

CHAPTER ONE

Radio Parts. General

1.1. Resistors

Resistors are used extensively in automatic control and signalling circuits, radio and television sets, etc., for maintaining specified conditions of operation of electronic valves, transistors, and other circuit elements.

Resistors are classified as:

(1) *wire-wound* and *composition* (*film-* and *solid-type*)—according to the method of manufacture employed;

(2) *fixed* and *variable*—according to the constructional and design features of the resistor;

(3) *general-purpose* and *special*—according to the field of application.

Resistors are specified by their *resistance*, *power rating*, and *resistance stability*.

The power rating depends primarily on the power that can be dissipated continuously in the resistor for an unlimited time without exceeding a permissible maximum temperature and determines the current-carrying capacity of the resistor.

Before connecting the resistor to a circuit, it is necessary to make sure that

$$P_R \geqslant I^2R$$

where P_R=power rating
I=current
R =value of the resistor

The stability of a resistor is determined by the change in resistance occurring with time and over a specified range of working temperatures.

Fixed composition resistors. These are available in a wide variety of types and designs. The most commonly used in control and test equipment are resistors with a

resistance element in the form of a carbon or metallic film deposited on an insulating base (usually a ceramic tube).

In particular, ВС, УЛМ, and МЛТ fixed resistors are of this make.

The letter symbols of the type designation indicate the kind of resistance element employed, the accuracy, stability, and other characteristics of the resistor. Thus, letters ВС stand for a high-stability resistor, УЛМ—for a carbon, varnished, small-size resistor, and МЛТ—for a metallized, varnished, heat-resistant resistor.

Fixed composition resistors are available in resistances of a few ohms to several hundred megohms, and in power ratings extending from fractions of a watt to several hundred watts.

Depending on the permissible deviation from the resistance marked on the body of the resistor, most general-purpose resistors fall into ± 5 per cent, ± 10 per cent, and ± 20 per cent classes.

The resistance of ВС, МЛТ, УЛМ, and other resistors varies with temperature. As an example, the resistance of МЛТ resistors may change by $\pm 1.2 \times 10^{-3}$ per cent per 1°C at changes in temperature from plus 25 to minus 60°C.

Variable composition resistors. These are used in numerous applications as adjusting and tuning elements. The most frequently encountered are СП and СПО resistors.

The type designation indicates: СП—a variable, composition resistor; СПО—a variable, composition, solid-type resistor.

The resistance element of СП resistors is a thin layer of graphite applied to and baked on a fibre or laminated bakelite base, and that of СПО resistors consists of a solid cylinder made of graphite mixed with a suitable binder.

A rotating slider travels over the resistance element and produces a continuous variation of resistance. The resistance that is introduced into the circuit depends on the angle between the slider and the movable contact of the resistor. The resistance element can be designed to give any resistance-rotation law desired (linear, logarithmic, or ex-

ponential). Variable composition resistors of different types are shown in Fig. 1.

Fixed wire-wound resistors. Wire made of an alloy of high resistivity (e.g., nichrome, constantan, manganin, etc.) is used for the resistance element of these resistors.

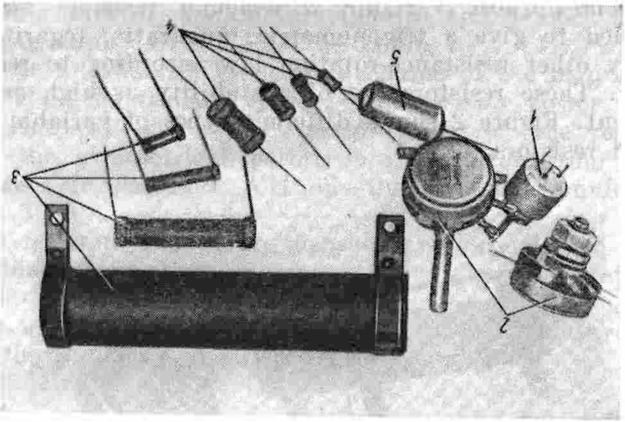


Fig. 1. Composition resistors

1 and *2* — СП-II and СПО-0,5 variable resistors; *3* — ВС fixed resistors of various power rating; *4* — МЛТ fixed resistors of various power rating; *5* — МГП high-ohm film resistor

The wire is wound on an insulating form of given shape and covered by a protective coating of vitreous-enamel, epoxy resin, or other insulating material.

Representative general-purpose fixed wire-wound resistors are those of the ПЭ, ПЭВ, and ПЭВР (wire-wound, enamelled, moisture-proof, adjustable) series.

In special cases when stringent requirements are to be met and a high stability is essential, use is made of precision resistors wound of 30-micron wire and having a stability of 0.5 to 0.003 per cent.

Variable wire-wound resistors. These are mostly of the continuously variable type made by winding resistance wire on an insulating base of ceramic, bakelite, plastic, or similar material and are used for adjusting measuring instruments, control circuits, etc.

Examples of general-purpose resistors of this kind are the РП-25 (25-watt, variable, wire-wound) and ППЗ (3-watt, variable, wire-wound) resistors. The resistance elements of these general-purpose resistors are usually made to follow a linear law of resistance change *vs* angular rotation of the slider.

Special-purpose variable wire-wound resistors may be designed to give a trigonometric, quadratic, logarithmic, or any other resistance-rotation law according to requirements. These resistors are of a stability as high as 0.01 per cent. Figure 2 shows different types of variable wire-wound resistors.

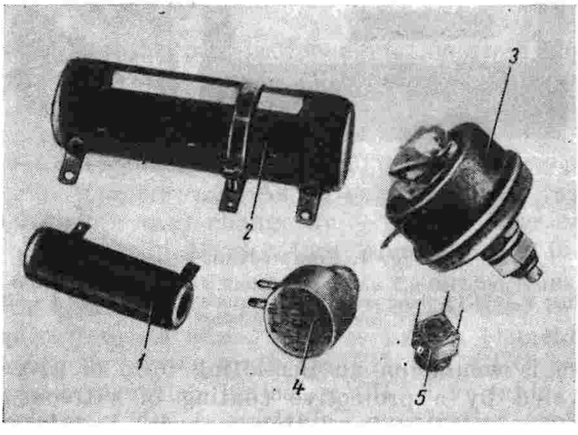


Fig. 2. Wire-wound resistors

1 — ПЭВ fixed resistor; 2 — ПЭВР adjustable resistor; 3 and 4 — РП-25 and ППЗ variable resistors; 5 — СП5-2 small-size variable resistor

Versions of variable wire-wound resistors are the rheostats commonly used in laboratory practice. Rheostats are produced in resistances from fractions of an ohm to several hundred ohms and in power ratings from tens of watts to several hundred kilowatts. Rheostats are made of resistance wire (nichrome, constantan, manganin, etc.) wound on a form with the beginning and end of the winding, as well as the slider lead brought out to the rheostat terminals.

The body of each resistor bears code markings indicating:
(1) the manufacturer's trade mark;
(2) the type of resistor;
(3) the power rating;
(4) the rated resistance;
(5) the permissible deviation from rated resistance;
(6) the date of manufacture (month and year).

For example, ВРЗ МЛТ 2 51 kohm 10% VII 68 is decoded as follows: ВРЗ—the trade name of the manufacturer; МЛТ—the resistor type; 2—the resistor power rating in watts; 51 kohm—the rated value of the resistor; 10%—the symmetrical permissible deviation from rated resistance in per cent; VII 68—the date of manufacture (July, 1968).

The resistors should be inspected periodically to make sure that their current-carrying parts are intact and to see that the code markings are legible.

The value of the resistance is checked by measuring it with the aid of a suitable ohmmeter.

1.2. Capacitors

Capacitors are used in measuring circuits for separating the variable and constant components of the circuit voltage, for smoothing voltage ripples in rectifier circuits, as elements of oscillatory circuits, for service in forming circuits, and many other applications.

Capacitors are classified as:

(1) *separating*, *coupling* (*stopping*), and *filtering*—according to the field of application;

(2) *mica*, *ceramic*, *paper*, *electrolytic*, and *air-type* —according to the dielectric used;

(3) *tubular*, *disc*, *moulded*, *sealed*, etc.—according to the constructional and design features of the capacitor.

Capacitors may be *fixed* or *variable*.

Capacitors are specified by their *capacitance*, *voltage rating*, and *capacitance stability*.

The voltage rating indicates the voltage that can be applied to the terminals of the capacitor for an unlimited period of time without breakdown of its dielectric.

Fixed capacitors. Most fixed capacitors have a capacitance tolerance (permissible deviation of capacitance from rated value) of ±5, ±10, and ±20 per cent, i.e., belong to the I, II, and III classes of capacitors, respectively. In exceptional cases, a capacitance tolerance of ±50 per cent may be assigned.

Mica capacitors are built up of alternating sheets of high-quality mica and metal foil. КСО capacitors of this type are enclosed in a moulded plastic casing. КСГ and СГМ capacitors have a sealed metal or ceramic casing.

КСО capacitors are available in rated capacitances from 51 to 30,000 picofarads and voltage ratings from 250 to 2,500 volts. КСГ capacitors are available in capacitances from 470 picofarads to 0.1 microfarad and voltage ratings up to 1,000 volts. СГМ capacitors are available in capacitances from 100 to 10,000 picofarads and voltage ratings as high as 1,500 volts.

Mica capacitors fall into 0, I, II, and III classes, providing for a capacitance tolerance of ±2, ±5, ±10, and ±20 per cent, respectively.

Ceramic capacitors made mostly of mixtures of titanium oxides with other titanates are of tubular (КТК capacitors) or disc (КДК capacitors) shape. The capacitor electrodes are formed by spraying and then firing two layers of silver on the ceramic tube or disc.

КТК and КДК capacitors are available in capacitances from 1 to 33,000 picofarads and voltage ratings up to 500 volts.

Paper capacitors are built up of layers of thin aluminium foil separated by kraft paper. The most generally used are КБГ-И and КБГ-МП—sealed paper capacitors manufactured in numerous modifications, БГМ—small-size sealed paper capacitors, and БМ—small-size paper capacitors.

Paper capacitors are produced in capacitances from 510 picofarads to 0.25 microfarad and voltage ratings up to 600 volts.

A version of paper capacitors is metallized capacitors. In this type a metallic film 0.01 to 0.05 micron thick is deposited on the dielectric (paper) in vacuum. Such capacitors are of smaller unit volume and weight as compared with ordinary paper capacitors. МБГО—sealed single-layer me-

tallized capacitors and МБМ—small-size metallized capacitors are widely used in measuring circuits.

Metallized capacitors are available in capacitances extending from 0.0051 to 30 microfarads and voltage ratings as high as 1,500 volts.

Electrolytic capacitors consist of three basic components: the anode, the dielectric film, and the electrolyte. The anode (positive electrode of the capacitor) is made of aluminium foil on which an oxide film (0.01-1.5 microns thick) serving as the dielectric is deposited by an electrochemical process. The cathode (negative electrode) is the electrolyte that is insulated from the anode by virtue of the oxide film formed on the latter. The oxide film has an asymmetric conductivity. The aluminium electrode must therefore always be connected to the positive side of the applied potential, and the electrolyte must always be negative. This circumstance allows electrolytic capacitors to be used only in direct and pulsating current circuits. These capacitors are used mainly in smoothing and decoupling filter circuits.

Measuring circuits usually employ КЭ—electrolytic capacitors, ЭГЦ—sealed cylindrical electrolytic capacitors, and ЭМ—small-size electrolytic capacitors.

In cases when high reliability, small size, and low weight are essential, use is made of tantalum capacitors. These capacitors have a positive electrode made of tantalum covered by an oxide film and employ an acid electrolyte as the negative electrode. Tantalum capacitors are manufactured in standard modifications ЭТ and small-size modifications ЭТО-I and ЭТО-II.

Electrolytic capacitors are available in capacitances from 0.5 to 2,000 microfarads and voltage ratings ranging from 6 to 500 volts.

Figure 3 shows some of the different types of fixed capacitors used for various purposes.

Variable capacitors. These are employed in frequency trimming, retuning resonant circuits, etc., and are made with air or some solid insulating material (mica, ceramics) as the dielectric. Some typical variable air-type and trimming capacitors (trimmers) are shown in Fig. 4.

The code markings on the body of the capacitor indicate:

(1) the manufacturer's trade mark;

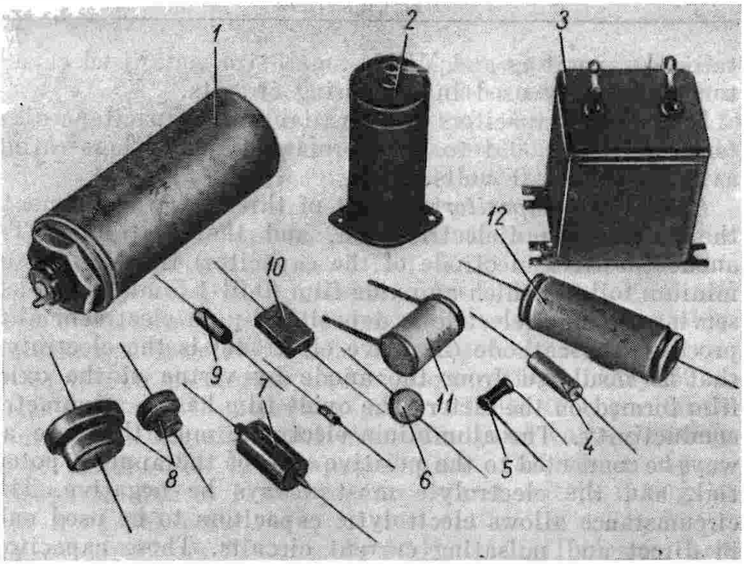


Fig. 3. Fixed capacitors

1 and *2* — КЭ-2 and ЭГЦ electrolytic capacitors; *3*, *4*, and *12* — МБГО and МБМ metallized capacitors; *5* and *6* — КТК and КДК ceramic capacitors; *7*, *9*, and *11* — БГМ, КБГ-И and БМ paper capacitors; *8* — ЭТО-I and ЭТО-II tantalum electrolytic capacitors; *10* — КСО mica capacitor

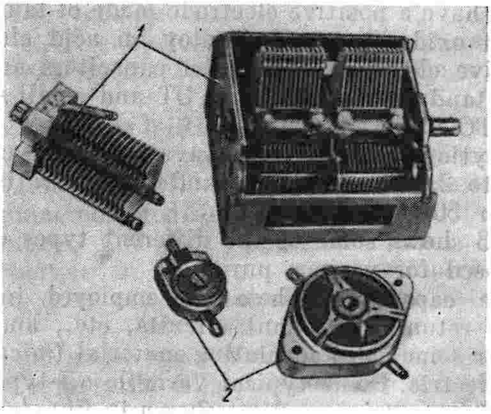


Fig. 4. Variable capacitors

1—air-type capacitors; *2*—ceramic trimming capacitors

(2) the type of capacitor;
(3) the capacitance value;
(4) the voltage rating;
(5) the capacitance tolerance;
(6) the date of manufacture (month and year).

For instance, МБМ 0.25 $\mu F \pm 20\%$ 500 V III 67 indicates: МБМ—the capacitor type; 0.25 μF—the capacitance value in microfarads; $\pm 20\%$ — the capacitance tolerance; 500 V—the voltage rating in volts; III 67—the date of manufacture (March, 1967).

An exception is small-size capacitors, the body of which bears only a marking indicating the value of the capacitance. In certain cases colour coding is practised.

The general condition of the capacitor is checked by visual inspection, special care being taken to see that the casing and terminals are not damaged in any way and the code markings are quite legible.

The capacitance is to be measured with the aid of a suitable capacitance meter.

The capacitor may be checked for internal short-circuits by means of an ohmmeter.

It should be kept in mind that connection to a voltage exceeding the voltage rating of the capacitor may cause total breakdown of the dielectric.

Electrolytic capacitors must be connected in strict accordance with the terminal polarity markings and never used in a.c. circuits.

1.3. Inductance Coils

Inductance coils are used for coupling high- and intermediate-frequency circuits, as high-frequency chokes, etc. The wide variety of high-frequency circuits encountered in practice and the dependence of their parameters on the constructional and design features of the coil call for an individual approach in selecting the latter for the circuit in question. In view of this circumstance, there is not much sense in series production of standard high-frequency coils.

High-frequency coils are conventionally specified by the value of their *inductance*, *distributed capacitance*, *quality factor* (*Q-factor*) and *stability*.

The Q-factor is defined as the ratio of inductive reactance to effective resistance and gives an idea of the ability of a coil to perform its primary function, that of supplying inductance at some given frequency. The inductive reactance—and, in consequence, the quality factor—vary with the coil inductance and the circuit frequency.

The stability of a coil is determined by the change in the Q-factor, inductance, and distributed capacitance occurring within the range of working temperatures and with time.

High-frequency coils may have a *single-layer* or *multilayer winding*. The coil windings are classified as *ordinary* and *universal*. The latter are more difficult to wind, but offer a lower distributed capacitance and are more robust. Single-layer coils are wound of insulated enamelled wire, and multi-layer coils, of silk-covered insulated enamelled wire.

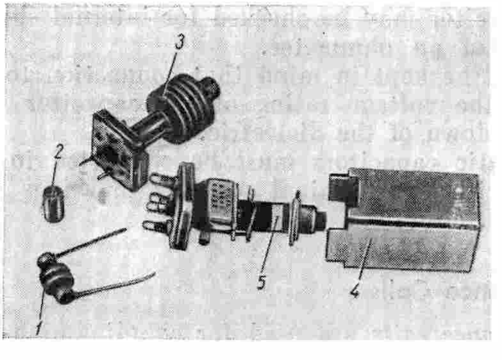


Fig. 5. Inductance coils

1—high-frequency choke with ordinary winding; *2*—trimmer core; *3*—coil with universal winding; *4*—magnetic shield; *5*—single-layer coil (with the shield removed)

Figure 5 shows several high-frequency inductance coils with different types of windings. In certain cases, the coils are sectionalized so as to improve their Q-factor and diminish the distributed capacitance.

To prevent undesirable coupling between coils and eliminate the influence of external fields it is common practice to surround the coils with a shield of conducting material.

The inductance of an air-cored coil can be significantly increased without changing the coil size if a ferromagnetic material, such as iron, is introduced into the winding. Use of ferromagnetic cores also makes it possible to adjust the coil inductance according to requirements.

As is known from physics, the magnetic properties of materials are primarily determined by their *relative permeability* μ. The relative permeability of ferromagnetic materials is hundreds and thousands of times higher than that of free space taken as unity. With the magnetic field strength H constant, the magnetic flux density B set up in the ferromagnetic material will accordingly be greater than that in free space by the same number of times:

$$B = \mu\mu_0 H$$

where μ_0 is the permeability of free space.

It follows from this equation that the inductance of a coil increases with introduction of a ferromagnetic core into the winding.

It should be noted, however, that the relative permeability of ferromagnetic materials is by no means constant and varies with the magnetic field strength, temperature, and magnetic losses due to hysteresis caused by cyclic magnetization of the core in an alternating magnetic field, i.e., with the frequency of the magnetizing current. The dependence on frequency is of prime importance and makes it necessary to select the core material in accordance with the frequency range for which the coil is intended.

The cores of coils meant for use in high-frequency circuits are usually moulded from magneto-dielectric or ferrite materials by special processing.

Magneto-dielectric materials (based on carbonyl iron, aluminium-silicon-iron alloys, etc.) are obtained by mixing the ferromagnetic material in finely powdered state with a dielectric powder and a suitable binder. The mixture is compressed at high pressures and baked to produce a very compact mass consisting of separate ferromagnetic partic-

les surrounded by a layer of dielectric. Cores of such structure offer a high electrical resistance and, consequently, have low hysteresis and eddy-current losses. This, in turn, improves the Q-factor of the coil and allows it to be used at higher frequencies.

Ferrite materials are chemical compounds of bivalent manganese, nickel, zinc, lithium, and ferric oxides. These materials have a relative permeability as high as 6,000 and resemble ceramics in hardness and brittleness. Therefore, ferrite cores should be protected against vibration and sharp impacts as these are liable to worsen the magnetic properties of the core.

1.4. Transformers and Low-Frequency Chokes

Transformers are widely used in low-frequency circuits as input and output matching elements, in pulse devices, in power supply circuits, etc.

Transformers are classified as:

(1) *mains*, *interstage* and *output transformers* and *pulse transformers*—according to the field of application;

(2) *open*, *shielded*, and *sealed*—according to their constructional and design features.

Chokes (or choke coils) are mostly used as rectifier filters, power supply filters, etc.

Transformers and chokes consist, basically, of a magnetic circuit and windings fitted on the limbs of the magnetic structure. Transformers and chokes are specified by the inductance and resistance of their windings, rated voltage, electric strength of the winding insulation, and the distributed capacitance. Transformers, in addition, are characterized by their ratio of transformation.

The *rated voltage* is defined as the voltage that can be safely applied to the transformer windings for an unlimited period of time without exceeding the permissible maximum temperature of the windings.

The *electric strength* of the winding insulation determines the ability of the transformer to withstand an applied voltage for an indefinitely long period of time without breakdown. The insulation strength is checked by apply-

ing a test voltage across adjacent windings and across the windings and the core (earth) of the transformer.

Electrostatic shields are often inserted between the transformer windings to reduce the capacitive coupling of the windings. The shield can be made by wrapping an incomplete turn of copper foil of the same width as the coil around the inner winding. In less important transformers, a layer of closely wound wire not more than 0.3 mm in diameter may be substituted for the sheet of copper foil.

Pulse transformers are widely used for transmitting pulses of short duration, inverting pulse phases, interstage coupling of pip amplifiers, etc. The design and structural material of pulse transformers are to be such as to provide for minimum distortion of the transmitted pulse.

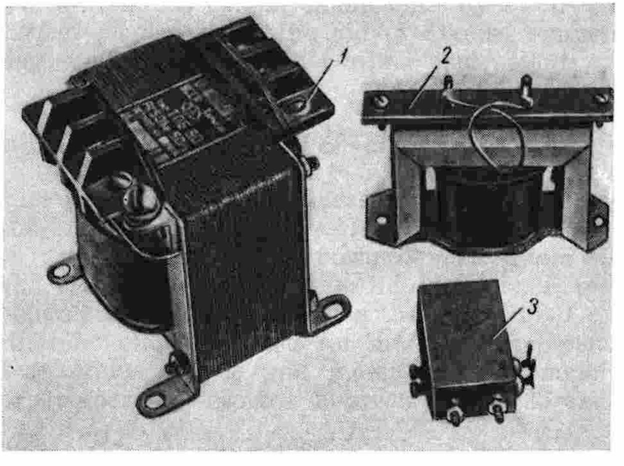


Fig. 6. Transformers and low-frequency chokes
1—step-down power transformer; 2—low-frequency choke; 3—sealed pulse transformer

Figure 6 shows different types of transformers and chokes used in practice.

REVIEW QUESTIONS

1\. 1. By what parameters are resistors specified?
1\. 2. How are resistors classified?
1\. 3. Name the main types of resistors.
1\. 4. Name the main types of capacitors.
1\. 5. What markings are made on the body of resistors and capacitors?
1\. 6. By what parameters are inductance coils specified?
1\. 7. What are the main types of inductance coil windings?
1\. 8. Name the applications of transformers and chokes.

CHAPTER TWO

Temperature Measuring Instruments

Proper processing of semiconductors calls for the maintenance of ambient temperatures and humidity at specified levels, thus making it necessary to carry out sufficiently accurate measurements of these parameters. Moreover, some of the technological operations involve temperature measurement of solids, air and gaseous mediums, including aggressive mediums.

Such measurements can be made both by *electrical* and *non-electrical methods* with the aid of diverse temperature measuring, controlling, and recording instruments.

2.1. Non-Electrical Measurement of Temperature

Non-electrical temperature measurements are made by means of *expansion thermometers*, the simplest and most common of which is the well known *liquid-in-glass thermometer* wherein a column of organic liquid (alcohol, toluene, pentane, etc.) or mercury serves as the indicator. Organic-liquid thermometers are used for measuring temperatures as low as minus 200°C, and mercury thermometers are used for temperature ranges between minus 25 and plus 500°C.

Liquid-in-glass thermometers are available in etched-stem and graduated-scale versions.

The etched-stem thermometer is a thick-walled capillary tube with a sealed upper end and with the working liquid in its bottom part (bulb); it has the scale graduations etched directly on the outer surface of the tube.

Thermometers of the second type have a separate graduated scale fixed to the capillary tube and placed together with the latter inside a protective glass case.

Mercury thermometers are manufactured only with a separate scale.

The measuring range of a thermometer is considered as being equal to the difference between the upper and lower limits of its scale. The value of one scale division is equal to the number of temperature degrees between two consecutive scale marks and is given by the ratio of the measuring range to the total number of scale divisions.

Thermometers are classified according to use as *laboratory-* and *industrial-type*. To avoid a loss of accuracy, laboratory-type thermometers must be entirely immersed into the body or volume whose temperature is being measured. In the case of industrial-type thermometers, it is sufficient to immerse the bulb, for which reason such thermometers are also referred to as emergent-stem thermometers.

The reading of a liquid-in-glass thermometer should be taken from the scale mark opposite the lower point of the working liquid meniscus. Temperature corrections must be applied to the readings of laboratory-type thermometers. The correction figures for the given thermometer may be found in its certificate.

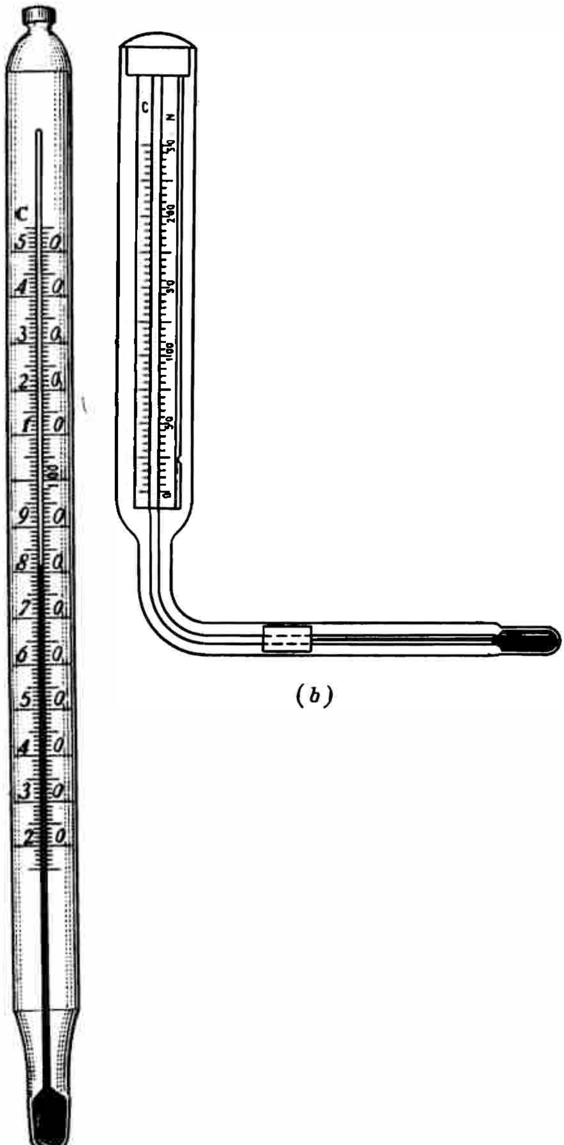
The lower part of industrial-type thermometers may be either straight (Fig. 7*a*) or bent at a right angle to the stem (Fig. 7*b*) for easier use.

In the case of thermometers having a mercury filling, electric contacts can be mounted on the stem wall to complete a circuit when the temperature reaches a specified value. These thermometers are called *contacting thermometers* and are used in alarm and control systems.

Contacting thermometers may be with sealed-in contacts or with a magnetically shifted contact.

In the first case, the contacts are sealed into the capillary tube and soldered to two copper leads (Fig. 8*a*). The circuit is closed as soon as the mercury column touches the contacts.

In the second case, the thermometer is fitted with two scales (Fig. 8*b*). The upper scale serves for setting the contact opposite the required temperature mark, and the lower scale, for measuring the temperature.

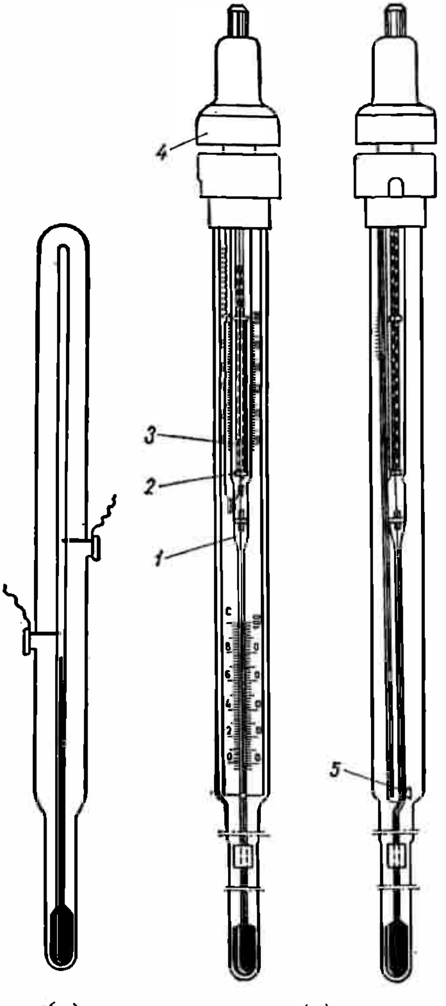


(a) (b)

Fig. 7. Industrial-type mercury thermometers
(a) straight-stemmed; *(b)* right-angled

A fine tungsten wire placed inside capillary tube *3* serves as movable contact *1* of the thermometer. This contact is moved upwards or downwards by oval-shaped nut *2* that travels along a guide screw enclosed in tube *3* of oval cross section. The guide screw is turned by means of permanent magnet *4* mounted on the top of the thermometer. Fixed contact *5* is sealed into capillary tube *3*. Contacts *1* and *5* are bridged by the mercury column when the preset temperature is reached.

Besides liquid-in-glass thermometers, expansion thermometers also include those of the *filled-system* or *manometric* type used mainly for remote measurement of the temperature of liquids and gases. The operation of these thermometers depends upon the variation of pressure with tempe-



(*a*) (*b*)

Fig. 8. Contacting thermometers

(*a*) with sealed-in contacts; (*b*) with a magnetically shifted contact; *1*—movable contact; *2*—oval-shaped nut; *3*—capillary tube; *4*—permanent magnet; *5*—fixed contact

rature of gases (usually nitrogen) or the saturated vapours of liquids filling a closed volume of space. The closed volume is made up of a hollow tube connected by a capillary tube to a bourdon tube (Fig. 9), and the entire system is filled with a gas or saturated vapour at a certain initial pressure.

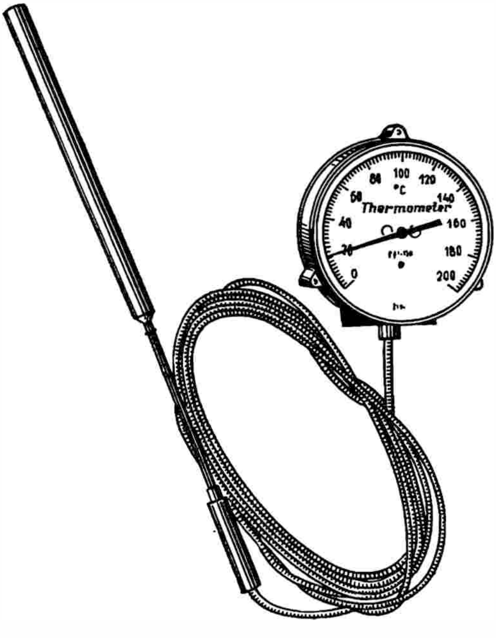


Fig. 9. Filled-system thermometer

The pressure in the filled system increases with rising temperature of the hollow tube. As a result, the bourdon tube uncoils and deflects the pointer of the temperature indicator.

Filled-system thermometers are often used for temperature control. In this case, they are usually fitted with two independent limit contacts mounted according to the range within which the temperature is to be kept.

Filled-system thermometers are designed for measuring temperatures up to 400°C.

2.2. Electrical Measurement of Temperature

Temperature as well as any other non-electrical quantity can be measured electrically by converting it into an electric signal proportionate to temperature. The converting device, known as a *transducer*, is connected to a suitable *indicating instrument* with a scale calibrated directly in terms of temperature units, i.e., graduated to read the temperature being measured.

Transducers. The transducers most commonly used for temperature measurements are resistance thermometers and thermocouples.

Resistance thermometers. Passage of current through a conductor is accompanied by release of heat that, in turn, affects the conductor resistance. At thermal equilibrium of the conductor and the surrounding medium, the temperature and, in consequence, the resistance of the conductor are determined solely by the conductor current and the conditions of heat exchange (i.e., the temperature, density, and velocity of the surrounding medium).

This dependence of the conductor resistance on temperature is utilized in resistance thermometers for measuring temperatures up to 500°C.

The temperature sensitive element of resistance thermometers is made of materials having a high temperature coefficient of resistance, such as copper and platinum. Copper, in particular, has a temperature coefficient of resistance equal to 0.00428 per °C.

The temperature sensitive element is in the form of a coil wound of thin copper or platinum wire of considerable length, the ratio of the diameter of the wire to its length being of the order of 1:500.

The resistance thermometer consists of a protective metal tube housing the temperature sensitive element, an aluminium cap containing the element terminals, and a threaded connecting sleeve for mounting the thermometer in place.

Usually, the temperature sensitive element is incorporated in a bridge network connected to a source of reason-

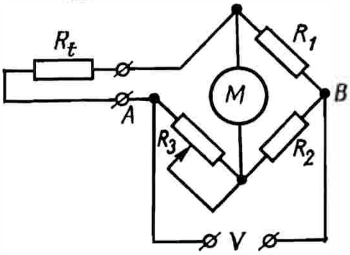


Fig. 10. Connection of resistance thermometer to bridge network

R_t—resistance thermometer; R_1, R_2, R_3—bridge arm resistors; M—measuring instrument; V—source of constant voltage

ably constant voltage. Figure 10 shows the temperature sensitive element R_t of the resistance thermometer inserted in one of the measuring bridge arms. Any change in the resistance of the temperature sensitive element throws the bridge out of balance and gives rise to a difference in potential between points A and B, thus setting up a flow of current through the measuring instrument M included in the diagonal of the bridge. The deflection of the instrument pointer is the greater, the greater the degree of unbalance of the bridge circuit.

Thermocouples. This type of transducer utilizes the Peltier effect for conversion of heat into electrical energy and can be used at temperatures up to 1,800°C.

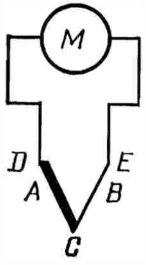


Fig. 11. Thermocouple circuit

A and B—dissimilar metals; C—hot junction; D and E—cold junctions

A thermocouple is fundamentally a pair of electrical conductors A and B of dissimilar materials that are welded together at junction point C (Fig. 11). If this junction is heated, a thermo-electromotive force roughly proportional to the temperature difference between junction C and the opposite ends D and E of the dissimilar conductors develops

across the junction. In consequence, a current will flow through the measuring instrument *M* and cause a certain deflection of its pointer. The scale of the instrument may be calibrated directly in temperature units. Junction *C* is called the *hot junction*, and junctions *D* and *E* are termed the *reference* or *cold junctions* of the thermocouple.

Measurements are made by placing the hot junction at the point where the temperature is to be measured and maintaining the cold junctions at a reference temperature of 0°C. Practically, the cold junctions are at an ambient temperature which is above zero. This makes it necessary to correct the instrument readings by finding the e.m.f. for the actual cold-junction temperature with the aid of a calibration chart and converting the instrument readings by means of the same chart into the e.m.f. developed by the thermocouple. The true temperature at the point of measurement is then obtained by reconverting the sum of the two values of e.m.f. with the aid of the same chart. This correction should be made in view of the fact that the e.m.f. is not directly proportional to the rise in temperature. In practical cases where an error of 0.5 to 1.0°C may be ignored, the temperature at the measured point can be found by simply adding the ambient temperature to the reading of the temperature measuring instrument.

Thermocouples are mostly a combination of the following materials: copper and constantan (for temperatures up to 300°C), chromel and copel (for temperatures up to 600°C), iron and copel (for temperatures up to 800°C), chromel and alumel (for temperatures up to 1,300°C), platinum and rhodium-platinum (for temperatures up to 1,600°C).

Indicating instruments. Ratiometers, millivoltmeters, and self-balancing potentiometers are the most commonly used for measuring temperatures by electrical methods.

Ratiometers. Permanent-magnet moving-coil ratiometers measure the ratio of two electrical quantities (currents or voltages) rather than their absolute values. The operation of ratiometers is based on the interaction of the field of a permanent magnet and the magnetic fields due to currents carried by two coils of the moving system of the instrument. The coils are fixed on a common spindle so that their position in relation to the field of the perma-

nent magnet and, consequently, the angular deflection of the instrument pointer are determined solely by the ratio of the coil currents. Ratiometers are used together with resistance thermometers.

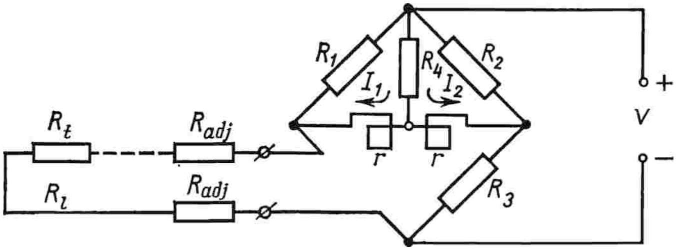


Fig. 12. Ratiometer and resistance thermometer connections
R_t—resistance thermometer; r—instrument coil resistances; R_{adj}—adjusting resistors; R_l— resistance of connecting leads; I_1 and I_2—coil currents; R_1 to R_4—bridge arm resistors

As may be seen from the circuit diagram of Fig. 12, the ratio of the currents I_1 and I_2 flowing through the moving system coils of resistance r depends solely on the resistance R_t of the thermometer and is independent of the source voltage V. The scale of the ratiometer is calibrated directly in terms of temperature units.

The measuring circuit is seen to include the resistance R_l of the thermometer connecting leads and adjusting resistors R_{adj} used for adjusting the external line resistance to the value R_{ext} indicated on the scale of the instrument.

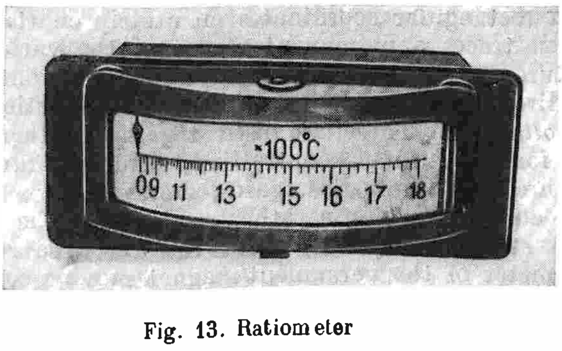


Fig. 13. Ratiometer

Ratiometers are used for measuring temperatures from minus 100 to plus 650°C. A typical indicating ratiometer is shown in Fig. 13.

Ratiometers are also available in temperature control and recording versions.

The temperature indicating and control ratiometer differs from the indicating ratiometer of Fig. 13 in that it has a two-position control device with "Lower" and "Higher" set temperature positions. When the set temperature is reached, the instrument pointer interrupts a beam of light cast upon a photoconductive cell of the temperature control device. The photoconductive cell is included in the circuit of an electromagnetic relay that opens its contacts when the cell current drops and disconnects the actuator of the temperature control system (heater, auxiliary relay, etc.) from supply. As a result, the temperature begins to drop and the pointer moves gradually to the left, thus allowing the beam of light to fall on the photoconductive cell. This re-energizes the relay and, consequently, the actuator of the control system.

The temperature control device may be made to have three operating positions ("Lower", "Standard", "Higher") and be of different design (say, with a cam-type contact closing mechanism).

Control and recording ratiometers have, in addition to the temperature measuring and control systems, a strip-chart mechanism for obtaining a continuous record of the changes in temperature with time. In these instruments, the pointer is replaced by a capillary pen that traces the record in rectangular coordinates on a strip chart.

The pen traces a permanent record of the variation of temperature with time on a paper chart moving continuously in a direction perpendicular to the pen deflection.

Millivoltmeters. These are used together with thermocouples for measuring, controlling, and recording the temperature of solid bodies, gases, etc.

Thermocouples develop a rather weak e.m.f. that can be measured satisfactorily only with the aid of a sensitive millivoltmeter of the permanent-magnet moving-coil type. The measuring circuit employed for this purpose is shown in Fig. 14. This circuit is made up of the measuring instru-

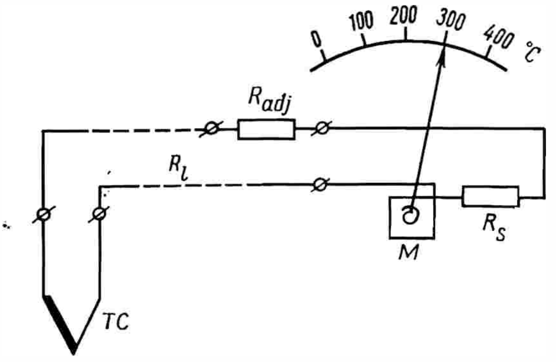


Fig. 14. Millivoltmeter and thermocouple connections
M—measuring instrument; R_s—series resistor; *TC*—thermocouple

ment M in series with resistor R_s, a thermocouple TC, connecting leads of resistance R_l, and an adjusting resistor R_{adj}.

The millivoltmeters may be provided with a recording mechanism and an electronic temperature control device. The latter consists of a control circuit comprising a coil mounted on the pointer indicating the set temperature, a high-frequency oscillator, and an electromagnetic relay furnished with a mercury contact.

The pointer of the millivoltmeter carries a duralumin shield that enters or leaves the gap between the sections of the control circuit coil so as to vary the circuit inductance. This change in inductance turns the high-frequency oscillator on or off, thus increasing or reducing the anode current of the valve driving the relay. As a result, the relay armature is drawn in or drops out and, consequently, makes or breaks the mercury contact.

The temperature control device may be of a two- or three-position type. In the latter case, it incorporates two control circuits, a twin high-frequency oscillator, and three electromagnetic relays. The output signal of such a control device depends on the resulting combination of the open and closed contacts of the relays.

Millivoltmeters are employed for the measurement and control of temperatures ranging from 0 to 1,800°C.

Self-balancing potentiometers. These are used with thermocouples* for high-accuracy measurement of temperature.

The operation of self-balancing potentiometers used for temperature measurement is based on the opposition method of e.m.f. measurement, whereby the e.m.f. developed by the thermocouple is balanced automatically by the voltage drop set up across a resistance by a flow of constant current supplied from an external source.

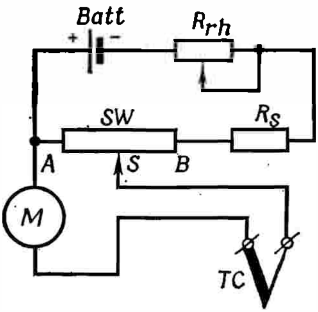


Fig. 15. Potentiometer and thermocouple connections

Batt—source of d.c. supply; *TC*—thermocouple; *SW*—slide wire; R_{rh}—rheostat; R_s—series resistor; *M*—measuring instrument

Figure 15 shows the basic circuit of such a potentiometer.

The circuit supply battery is connected to a slide wire (calibrated resistance) *SW* through an adjusting rheostat R_{rh} that serves for maintaining a constant potential difference between points *A* and *B* of the slide wire. The thermocouple *TC* is connected so that its e.m.f. acts in opposition to the battery e.m.f. The measuring instrument *M* can be brought to equilibrium by shifting the sliding contact *S* along the slide wire until the voltage drop across *AS* counterbalances the e.m.f. developed by the thermocouple.

This motion of the sliding contact is effected by a follow-up system that balances the e.m.f. and the voltage

* Self-balancing potentiometers may also be used in joint with radiation pyrometers measuring the temperature of solid bodies according to the rate of energy emission per unit area of the heated surface of the body.

drop automatically so that no current flows through the measuring instrument (e.g., a galvanometer).

The follow-up system is actuated by an amplifier that amplifies the unbalanced voltage. The sliding contact is linked either with the pointer, a movable scale or the recording mechanism of the potentiometer.

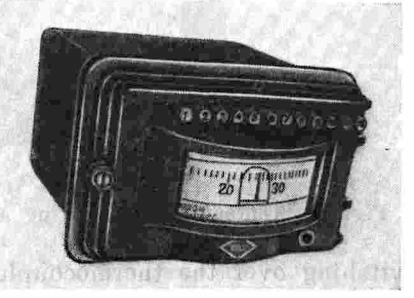


Fig. 16. Temperature indicating potentiometer

Figure 16 shows a typical temperature indicating potentiometer. This instrument has a fixed pointer and a drum-type scale driven by an electric reverse motor that is actuated by the amplifier of the temperature control system. The scale can be rotated through an angle of nearly 360°. These potentiometers can be used to measure temperatures with an accuracy of ± 0.5 per cent.

Figure 17 shows a temperature indicating and recording potentiometer. The upper part of this instrument has a horizontal scale graduated to read the temperature. The pointer moving along the scale is fitted with a pen that simultaneously traces the variation of temperature with time on a strip chart travelled vertically at a constant speed. This potentiometer is used for making measurements accurate to ± 0.5 per cent.

Self-balancing potentiometers are capable of controlling and measuring the temperature at several different points (3-, 6-, 12-, and 24-point versions). Such instruments are connected to a number of thermocouples according to the points to be measured and are provided with means for

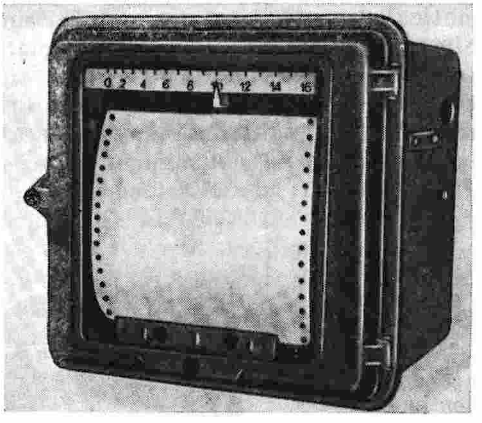


Fig. 17. Temperature indicating and recording potentiometer

switching over the thermocouples automatically in a pre-established order.

Thermocouple instruments are of complicate design and should be handled in strict compliance with the operating instructions and rules set forth by the manufacturer. These rules stipulate the parameters that can be measured by the given instrument and specify the ambient temperature, relative humidity, atmospheric pressure, and surroundings for which the instrument is meant. The operating instructions also contain information regarding the external connections to be made and the manner in which the instrument is to be mounted and used. One of the main requirements for proper installation is that the instrument should be kept away from external magnetic fields liable to worsen the sensitivity of its permanent-magnet moving-coil system. In cases when this requirement cannot possibly be met, measures recommended by the manufacturer should be taken to protect the instrument against the harmful effect of these fields. The manufacturer's instructions also specify the periodicity of lubrication and the points to be lubricated.

The temperature measuring instruments are to be regularly inspected in accordance with local rules.

REVIEW QUESTIONS

2.1. Describe the electrical and non-electrical methods of temperature measurement in common use.

2.2. Name the main instruments used for non-electrical measurement of temperature.

2.3. What is the basic principle of transducers used for temperature measurement?

2.4. Explain the operation of indicating instruments used in joint with transducers for electrical measurement of temperature.

CHAPTER THREE

Semiconductor Devices and Their Applications

3.1. General

Semiconductor devices perform exactly the same functions as electronic valves (vacuum tubes) and distinguish favourably from the latter by their much smaller size and weight, low power consumption, absence of filaments, and inherent disadvantages (long heating time, heater cathode hum, etc.), high resistance to vibration and, above all, their long service life and, consequently, high reliability. These advantages have led to the widespread use of semiconductor devices in all kinds of radioelectronic and automatic control circuits. Just a few examples are their application to modern computers, automatic drive systems, transmitter-receiver sets, and radar installations.

Semiconductor devices are made of germanium, silicon, gallium arsenide, selenium, and other semiconductor materials employed in the form of crystals that are to be as flawless and impurity-free as possible. The permissible content of impurities does not exceed 10^{12} atoms per cm^3 or, in other words, there should be not more than one impurity atom in 10^{10} atoms of the basic semiconductor material.

Figure 18 gives a two-dimensional representation of the lattice structure of a germanium crystal. As may be seen from the drawing, each atom of the lattice forms covalent or electron-pair bonds with four neighbouring atoms. A crystal in which all the atoms are tied together by such bonds (i.e., a crystal with all bonds filled) will be electrically neutral.

If the covalent bond is broken as shown in Fig. 18*b* (say, by thermal agitation due to a rise in temperature), one of the electrons is released from the bond and will be free to roam through the material, i.e., becomes a *free electron*.

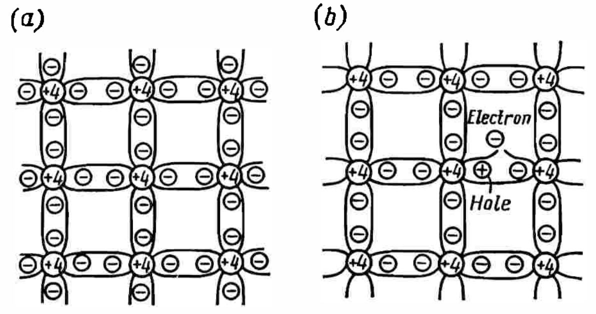


Fig. 18. Two-dimensional representation of germanium lattice (a) with all bonds filled; (b) with a broken bond creating a hole-electron pair

The vacancy thus formed in the bond is called a *hole* and has the statistical properties of a positive particle carrying a charge equal in magnitude and opposite in sign to that of the electron.

In the absence of an externally applied electric field, the holes move chaotically for some time after their appearance until they eventually recombine with one of the free electrons (re-fill the covalent bond). In cases when an external field is applied to the crystal, the holes and electrons begin an orderly movement in opposite directions determined by the direction of the field.

Thus, it is evident that semiconductor materials feature two different types of conductivity. The conductivity due to the motion of electrons is known as *electron* or *n-type** conductivity of the material. The conductivity caused by the motion of holes is termed *hole* or *p-type*** conductivity. The electron and hole conductivity resulting from the rupture of covalent bonds is referred to as *intrinsic*.

The conductivity of a semiconductor can be varied according to requirements by intentionally introducing minute amounts of a specific impurity in the crystalline structure of the material. These impurities are usually

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* The letter n stands for "negative" charge carrier.
** The letter p stands for "positive" charge carrier.

selected from the IIIrd and Vth groups of the periodic table of elements.

Thus, *p*-type conductivity is obtained by adding such group III elements as boron, indium, and aluminium. Figure 19*a* shows a trivalent impurity atom of indium (represented by the encircled +3 symbol) surrounded by tetravalent germanium atoms. The indium atom is incapable of forming the fourth covalent bond with one of the

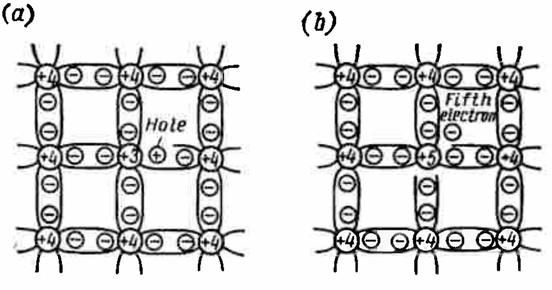


Fig. 19. Two-dimensional representation of (*a*) indium- and (*b*) antimony-doped germanium lattice

germanium atoms and becomes an immobile negatively-charged ion. The vacancy that exists in the fourth bond creates a hole in the lattice. Semiconductors of such crystalline structure have an excess of holes and, consequently, exhibit *p*-type conductivity. Impurities producing this type of conductivity are called *acceptors*.

N-type conductivity is obtained by adding such group V elements as antimony, arsenic, and phosphorus. Figure 19*b* shows how one pentavalent antimony atom forms covalent bonds with four germanium atoms, leaving the fifth valence electron unbonded, i.e., free to move through the semiconductor.

Such semiconductors have a surplus of electrons and, consequently, *n*-type conductivity. Impurities producing this type of conductivity are called *donors*.

In *p*-type semiconductors the holes constitute the *majority carriers* (mobile charge carriers responsible for conductivity), whereas in *n*-type semiconductors the majority carriers are electrons.

Let us consider the case where a junction is formed by bringing a p-type semiconductor into contact with an n-type semiconductor so that there is an abrupt transition from p- to n-type conductivity at the boundary. This is achieved by alloying a segment of p-type material to another segment of n-type material or, alternatively, by growing a single crystal in which the acceptor impurity is made to predominate in one part as the crystal is drawn out of a suitable melt and the donor impurity is made to predominate in the other part.

The boundary of the p- and n-regions is called an *electron-hole* or *p-n junction*. As the p-type semiconductor has a relatively high concentration of holes (electron vacancies) while the n-type semiconductor has a high concentra-

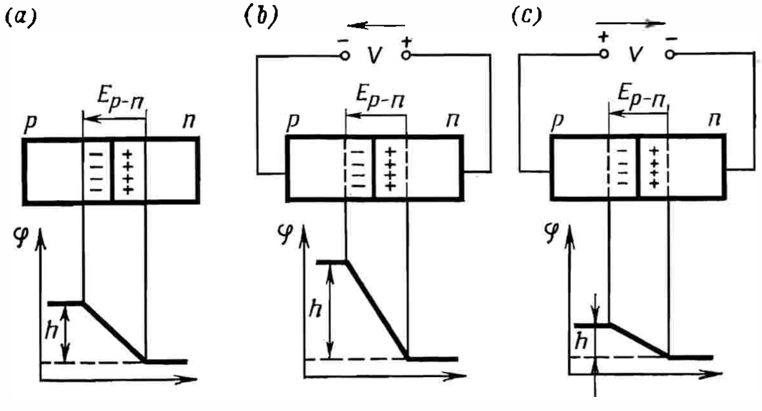


Fig. 20. Electric potential diagram for a p-n junction

(a) in the absence of an externally applied electric field; (b) with the externally applied field acting in the direction of the junction field; (c) with the externally applied field acting against the junction field

tion of electrons, there will be a tendency for the electrons to diffuse over to the p-side and for the holes to diffuse over to the n-side of the junction as shown in Fig. 20.

This exchange of holes and electrons between the p- and n-regions produces a layer of positive charges on the n-side and of negative charges on the p-side of the junction, thus giving rise to an electric field $E_{p\text{-}n}$ directed

from the n-region towards the p-region (Fig. 20*a*). This electric field — referred to as the p-n junction field — creates a deficiency of majority carriers on either side of the junction. The region lacking majority carriers is called the *depletion region* or *barrier layer* of the junction and presents a high ohmic resistance to majority carriers. The electric field surrounding the p-n junction increases the mobility of the *minority carriers*.

The width of the barrier layer may be from fractions of a micron to several microns depending on the resistivity of the semiconductor.

When a voltage V is applied to the junction terminals in such a polarity as to make the n-region positive and the p-region negative, the external field set up by the applied voltage acts in the same direction as the p-n junction field.

In this case, the majority carriers are attracted to the positive terminal away from the barrier layer, the potential barrier increases, and the majority carrier current flowing through the p-n junction is correspondingly reduced. At a specific value of the applied voltage, the current passing through the junction will be due only to the contribution of the minority carriers (Fig. 20*b*). This minority carrier current is known as the *reverse current* of the junction.

When the applied voltage is reversed, making the p-region positive and the n-region negative (Fig. 20*c*), the electric field of the p-n junction acts against the external field. In consequence, the current flowing through the junction will be constituted of majority carriers. This majority carrier current is called the *forward current* of the junction.

Thus, the magnitude and direction of the current passed through the p-n junction is seen to depend on the magnitude and direction of the applied voltage.

These properties of the p-n junction are at the basis of modern semiconductor engineering.

Semiconductor devices are of two principal types: *diodes* and *transistors*.

These devices are classified according to:

Classification of Semiconductor Diodes According to Application

- Semiconductor diodes
  - Rectifier diodes rated up to 0.1 MHz
  - High-frequency diodes rated from 0.1 to 1,000 MHz
  - Microwave diodes rated above 1,000 MHz
  - Pulse diodes
  - Reference diodes
  - Controlled and uncontrolled switching diodes
  - Variable capacitance (varicap) diodes
  - Tunnel (Esaki) diodes
  - Photodiodes and lasers

Classification of Transistors According to Application

- Transistors
  - Low-frequency transistors rated up to 0.1 MHz
  - High-frequency transistors rated from 0.1 to 1,000 MHz
  - Microwave transistors rated over 1,000 MHz
  - Pulse transistors
  - Phototransistors

(1) the method of production of the *p-n* junction—as *junction* (diffused, alloyed, etc.) and *point-contact*;

(2) design features—as *standard* and *special-purpose* (say, tropical model);

(3) diode power rating—*low-power* (mean forward current $I_{for}<0.3$ ampere), *medium-power* ($0.3 \leqslant I_{for} \leqslant 10$ amperes), and *high-power* ($I_{for} \geqslant 10$ amperes);

(4) transistor power rating—*low-power* (maximum permissible collector power $P_c<0.3$ watt), *medium-power* ($0.3 \leqslant P_c \leqslant 5$ watts), and *high-power*($P_c>5$ watts).

Semiconductor devices are also classified according to their applications. This classification is presented on page 43.

3.2. Semiconductor Diodes

Semiconductor devices rely for their operation on the physical processes taking place in the *p-n* junction. Figure 21 illustrates the volt-ampere characteristics of a semiconductor diode, i.e., the dependence of the current

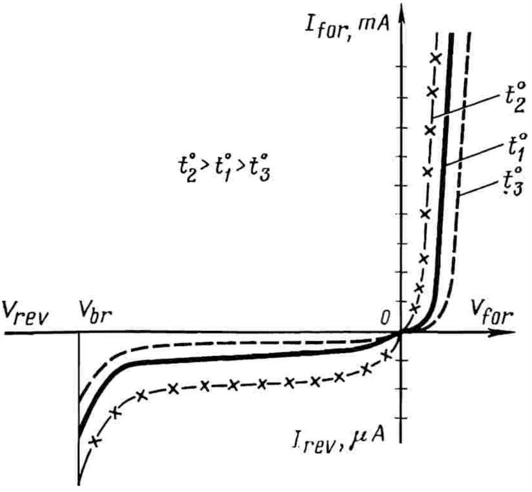


Fig. 21. Set of diode volt-ampere characteristic curves

passed through the diode on the applied voltage. The curves to the left of the ordinate axis represent the so-called *reverse characteristics*. These curves describe the diode current for the case when the voltage is applied so as to make the n-region of the junction positive and the p-region negative. Under such conditions, the diode is said to be reverse-biased or, in other words, the junction is connected to *reverse voltage* V_{rev}. The reverse current maintained by the reverse voltage is due solely to the movement of minority carriers set up by this voltage. It is very weak and, say, for commonly used medium-power diodes does not exceed 0.3 milliampere on connection to a reverse voltage of 400 volts.

When the reverse voltage attains a certain critical upper-limit value V_{br} known as the *breakdown voltage* of the diode, the p-n junction is punctured and, as a result, its ohmic resistance drops abruptly. When this happens, the diode becomes conducting in the reverse direction, thus losing its rectifying property.

The curves on the right-hand side of the ordinate axis represent the *forward characteristics* obtained when the diode is under forward bias, i.e., the *forward voltage* V_{for} is applied to the junction. The resulting forward current I_{for} is due to the passage of majority carriers through the junction and, as may be seen from the plot, under these conditions the diode current increases sharply with increasing voltage; for common medium-power diodes it attains several hundred milliamperes. The forward voltage V_{for} is determined by the forward resistance of the diode and in the case of common medium-power diodes is of the order of one volt. The forward current I_{for} is non-linearly related to the forward voltage V_{for}, this meaning that the diode offers a non-linear resistance to the forward current. The lower part of the forward curves has a threshold (the curve 'knee') after which the current rises sharply. The voltage applied to the diode before the threshold is reached is spent in overcoming the resistance of the internal electric field (space charge) of the p-n junction.

Figure 21 shows the volt-ampere characteristics of a semiconductor diode for different temperatures. The energy of the charge carriers, the number of free electrons and

holes (minority and majority carriers), and the forward and reverse currents flowing through the junction increase with rising temperature. By virtue of these factors, the reverse section of the volt-ampere curve for higher temperatures is located below and the forward section is to the left of the curve for lower temperatures. The set of volt-ampere characteristic curves depicted in Fig. 21 applies to rectifier, high-frequency, microwave, and pulse diodes.

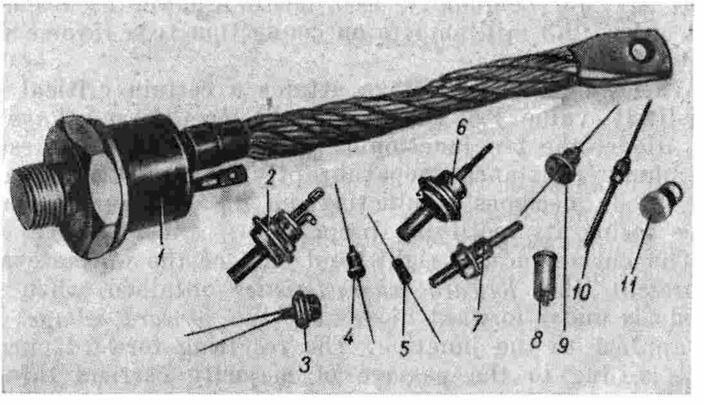


Fig. 22. Semiconductor diodes

1, *2*, and *3*—high-, medium-, and low-power controlled diodes; *4* and *7*—medium- and low-power reference diodes; *6* and *9*—medium- and low-power rectifier diodes; *5* and *10*—high-frequency diodes; *8*—microwave diode; *11*—laser diode

Figure 22 shows different types of available semicon ductor diodes, and Figure 23 shows some typical diodes The code markings are made on the body of the diodes and on the terminals of small-size diodes. The marking is usually done in the form of inscriptions, with the exception of high-frequency diodes where a colour coding is resorted to because of the small size of the diode cases and terminals. The code marking indicates the manufacturer's trade mark and specifies the type of the given diode, as well as the date of its manufacture.

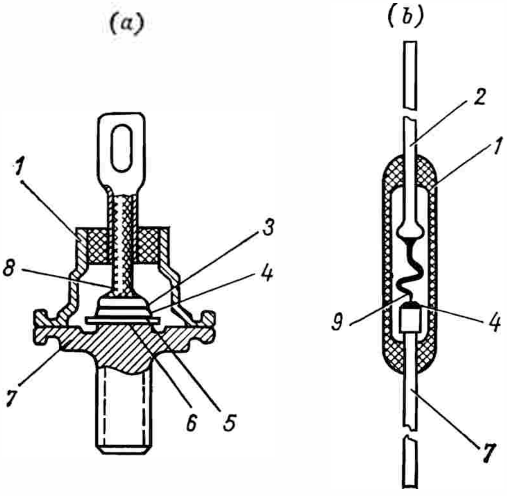


Fig. 23. Typical construction of semiconductor diodes
(a) junction rectifier diode; (b) point-contact high-frequency diode; 1—case; 2—rigid lead; 3 and 5—solder; 4—silicon crystal with p-n junction; 6—tungsten temperature compensator; 7—crystal support; 8—flexible lead; 9—tungsten contact whisker

Rectifier diodes are used for rectifying alternating currents (Fig. 24). The operation of these diodes is based on the unidirectional conductivity of the *p-n* junction. Figure 24*b* shows the waveform of the rectified current flowing through the load connected to the output of the rectifier. When the forward voltage (the positive half cycle

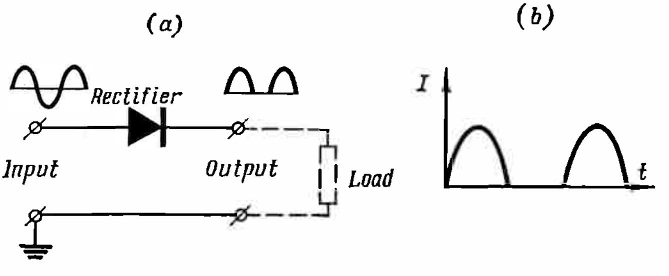


Fig. 24. Rectifier diode
(a) rectifier circuit; (b) waveform of the rectifier output current

of the alternating current) is applied to the diode, the rectified current waveform is the same as that of the applied a.c. voltage. Throughout the negative half cycle the diode current is zero (the effect of the reverse current may be ignored). Rectifier semiconductor diodes are usually employed in low-frequency circuits (at frequencies from 50 to 2,000 hertzes). To ensure a high efficiency of the rectifier operation, the forward voltage drop V_{for} across the diode due to the flow of forward current must be made as small as possible.

Rectifier diodes are capable of handling forward currents ranging from tens of milliamperes to tens and hundreds of amperes and reverse voltages from tens to thousands of volts.

Rectifier diodes are usually specified by the following parameters:

(a) rectified current or mean forward current I_{for} averaged over a whole cycle of the alternating current;

(b) mean forward voltage drop V_{for} averaged over a whole cycle of the supply voltage;

(c) maximum permissible reverse voltage V_{rev};

(d) maximum reverse current I_{rev} passed by the diode on applying the maximum permissible reverse voltage.

High-frequency and microwave diodes may be used for various purposes, such as rectification of alternating currents within a wide range of frequencies (up to several thousand megahertzes), detection, modulation, and other conversion of electric signals.

High-frequency and microwave diodes are specified in the same way as rectifier diodes by their mean forward current, mean forward voltage, maximum reverse voltage and current. Besides that, these diodes are also characterized by the range of working frequencies Δf, the capacitance C_d, and the quality (Q-factor) of the diode.

Pulse diodes are employed for producing pulses of short duration and transient periods (microseconds and tenths or even hundredths of a microsecond) at relatively high values of the forward current (equal to and over 50 milliamperes).

The time required for transient recovery of the processes occurring when the diode in question is switched over

from open (forward bias or "ON") to cut-off (reverse bias or "OFF") state and vice versa must be taken into account. Figures 25 and 26 illustrate the dependence of the circuit current and voltage on the time needed for the diode to become forward- or reverse-biased.

When the diode is switched from the "OFF" to the "ON" state, the transition of the circuit voltage from zero to steady-state value is not instantaneous but requires a defi-

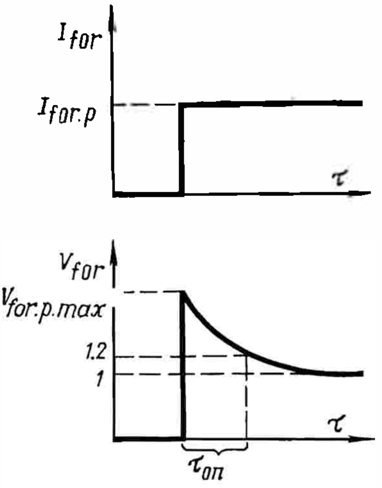


Fig. 25. Forward recovery of pulse diode

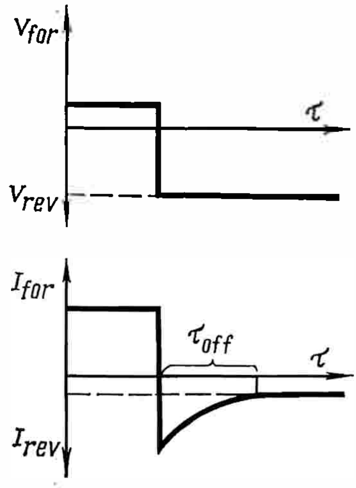


Fig. 26. Reverse recovery of pulse diode

nite period of time. The time τ_{on} that elapses from the appearance of the forward current pulse to the moment when the voltage across the load connected in series with the diode drops to 1.2 of steady-state value is called the *forward-recovery* or *turn-on time* of the diode (Fig. 25).

The ratio of the peak value $V_{for.\,p.\,\max}$ to the forward pulse current $I_{for.p}$ is called the *maximum pulse resistance* $R_{p.\max}$ of the diode.

Similarly, transition from the "ON" to the "OFF" state does not occur instantaneously (Fig. 26) as the base of the diode acquires a certain charge during the preceding

flow of forward current. At application of the reverse voltage, the charge disperses and gives rise to a pulse current that may be several times greater than the steady-state reverse current. The time τ_{off} in the course of which the diode current drops to specified value after reversing is called the *reverse-recovery* or *turn-off* time of the diode.

Reference (voltage stabilizing) diodes possess volt-ampere characteristics of the type shown in Fig. 27. The forward characteristic of these diodes is similar to that of rectifier diodes (see Fig. 21), whereas the reverse characteristic differs in that beginning from a specific value of the reverse voltage, known as the *stabilizing voltage* V_{st}, the voltage drop across the diodes becomes practically independent of current. The working part of the volt-ampere characteristics of these diodes is represented by section *CD* of the characteristic curve.

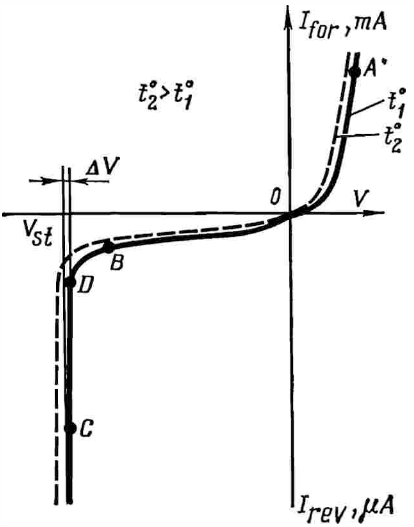


Fig. 27. Volt-ampere characteristics of reference diode

Silicon-junction reference diodes are, basically, of the same structure and design as rectifier diodes. Reference diodes serve for stabilizing voltages or currents in networks subject to load resistance or supply voltage fluctuations.

Reference diodes may also be used for shaping square pulses, pulse limitation, and overload protection of measuring instrument circuits.

Circuits employing this kind of diode for pulse limitation and milliammeter overload protection are shown in Figs 28*a* and *b*.

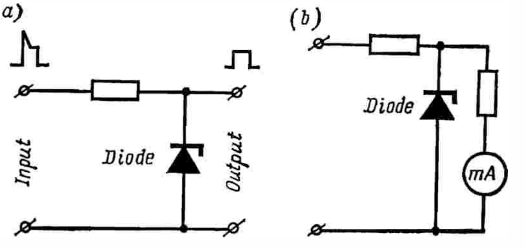


Fig. 28. Reference diode circuits
(a) pulse-limiting circuit; (b) milliammeter overload protection circuit

Switching diodes are built up of four p- and n-type semiconductors constituting three p-n junctions. For this reason, these diodes are sometimes also referred to as *four-layer diodes*.

The volt-ampere characteristic of a switching diode (Fig. 29a) has a region AB of negative resistance, a region BO within which the diode is non-conducting in the forward direction, a reverse working region OD, and a forward working region AC.

When a d.c. voltage above a specific value V_{on} is applied across the anode A and cathode K (Fig. 29b), the diode becomes conducting, i.e., is switched to the "ON" state. In consequence, the voltage across the diode sharply reduces and the current in this circuit depends practically only on the value of resistor R_a. Under these conditions, the diode operates on the nearly vertical section of the characteristic curve. The voltage V_{on} creating such conditions is called the *turn-on* or *opening voltage* of the diode.

The diode is switched "OFF" by reducing the current below a certain *holding value* corresponding to I_h. The four-layer junction is made conducting by applying a d.c. control voltage V_2 to the inner p-type layer (Fig. 29c). In this case the diode switching voltage drops sharply as shown by the broken line AO of Fig. 29a. The switching current is referred to as the diode *control current*. This current flows from the inner layer of p-type conductivity (known as the *control electrode*) to the cathode K of the diode.

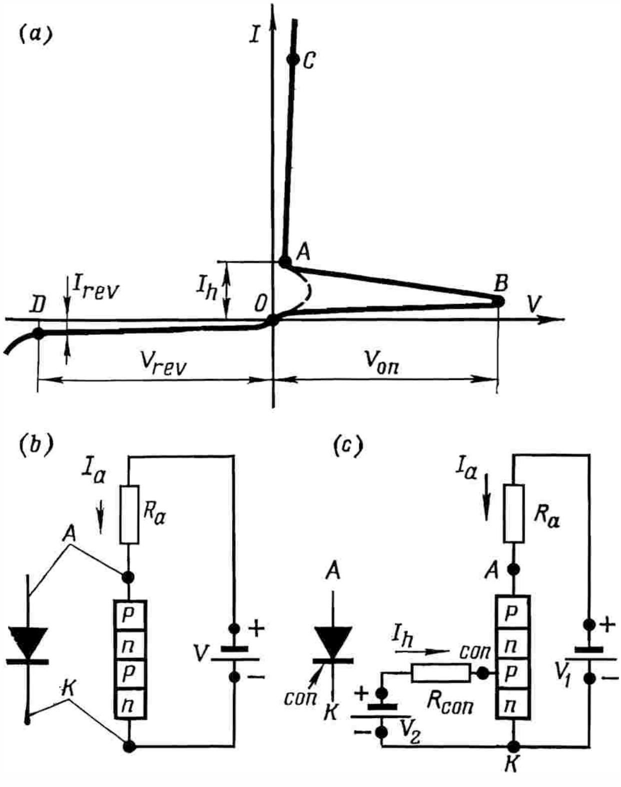


Fig. 29. Switching diode

(a) volt-ampere characteristic (the broken line represents the rectified section of the characteristic curve); (b) uncontrolled diode circuit; (c) controlled diode circuit

Controlled diodes are cut off with no control current flowing and at a forward current smaller than the holding current I_h.

Uncontrolled switching diodes are called *dinistors*, and controlled diodes are known as *thyristors*.

Other types of semiconductor devices having a four-layer structure are *turn-off thyristors* and *semistors*. The first have a volt-ampere characteristic similar to that of

thyristors and are switched "OFF" by delivering positive or negative pulses to a special control electrode without necessarily changing the forward current. Semistors have a forward characteristic similar to that of thyristors, and a reverse characteristic that is a mirror image of the forward characteristic. Semistors are controlled in the same manner as thyristors.

In recent years, switching diodes have found a wide variety of applications. They are used in automatic control circuits for noncontact (static) switching of actuating mechanisms, in high-power controlled sources of d.c. supply, in electric generator circuits, in pulse shaping and forming circuits, etc.

Variable capacitance diodes (varicaps). These semiconductor diodes known also as varactors have a capacitance that varies inversely from several tens to several hundreds of picofarads with increasing reverse voltage. Variable capacitance diodes are used in parametric amplifier, oscillator, and other radio circuits.

Tunnel diodes, or *Esaki diodes* as they are sometimes called, hold a distinctive position among semiconductor diodes. The operation of these diodes is based on the tunnel effect of quantum mechanics by which moving particles (in our case, electrons) become capable of penetrating a finite barrier (here, the *p-n* junction) of higher potential energy than their kinetic energy.

This effect shows up when a strong electric field is applied to a very thin *p-n* junction (about a hundred times thinner than the junctions of ordinary semiconductor diodes). Such junctions are produced by heavily doping the semiconductor material so as to obtain a concentration of about $5 \cdot 10^{19}$ impurity atoms per cm^3 of the semiconductor.

The volt-ampere characteristic of a tunnel diode (Fig. 30) features a region AB of differential negative resistance. Point A of the characteristic curve determines the values of the current and voltage corresponding to the peak (maximum) of the volt-ampere curve (I_{max}, V_{peak}), and point B gives the current and voltage for the curve minimum (I_{min}, V_{min}). Point C determines the value of the maximum voltage V_{max} appearing across the diode during the passage of a current equal to I_{max} through the junction.

3.3. Transistors

Basically speaking, the transistor is a circuit element used for amplification of electric signals by controlling the flow of charge carriers passed through a semiconductor crystal.

The transistor is composed of two *p-n* junctions formed by two regions of similar conductivity separated by a region having a different type of conductivity.

Transistors may be of *p-n-p* or *n-p-n* types differing in the sequence of the junctions (Fig. 31). The physical processes are the same in both types of transistors.

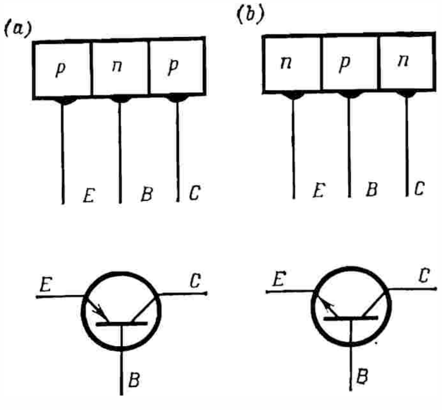


Fig. 31. Symbolic representation of (*a*) *p-n-p* and (*b*) *n-p-n* transistors

The region emitting the carriers is called the *emitter* (denoted by letter *E*), the region collecting the carriers is called the *collector* (denoted by letter *C*), and the region between them is called the *base* (denoted by letter *B*) of the transistor.

The arrowhead in the symbolic drawing of the transistor indicates the direction of current flow in the emitter.

Figure 32 shows some of the transistors in common use.

With no external voltage applied to the terminals of the transistor, i.e., with the transistor at equilibrium, the

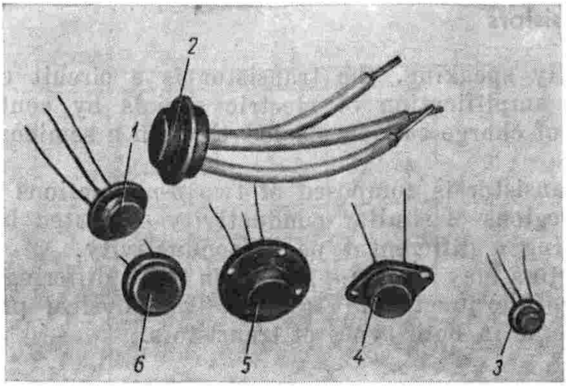


Fig. 32. Typical transistors

1—medium-power high-frequency transistor; 2—high-power low-frequency transistor; 3—low-power low-frequency transistor; 4, 5, and 6—medium-power low-frequency transistors

potential diagram of the junctions under consideration will be as illustrated in Fig. 33*a*. As in the case of a single *p-n* junction, the potential barriers set up at the emitter-base and base-collector junctions prevent penetration of majority carriers into the neighbouring regions. In other words, the internal field potential drops across the emitter-base junction and rises across the base-collector junction.

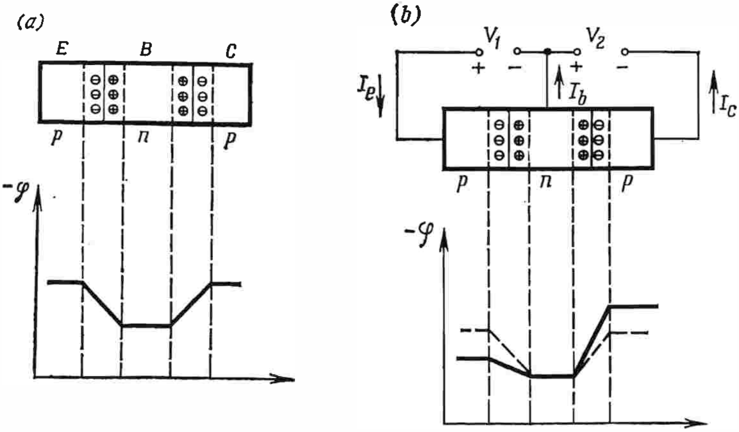


Fig. 33. Potential diagram for *p-n-p* transistor

(*a*) under conditions of equilibrium; (*b*) with forward bias applied

Application of a forward voltage V_1 makes the emitter-base junction conducting, thus lowering the internal field potential of the left-hand junction (Fig. 33*b*) and initiating a movement of holes from the *p*-region (emitter) into the *n*-region (base) of the transistor. The base region being very thin, the majority carriers of high kinetic energy are capable of diffusing into the collector region. As the cut-off voltage V_2 (generally, $V_2 \gg V_1$) applied to the collector junction produces an accelerating field, holes in the vicinity of the base-collector junction will be captured by this field and transferred into the collector region, thus setting up a flow of current in the collector circuit.

Relation between transistor currents. This relation will further be discussed with reference to a *p-n-p* transistor.

As mentioned above, most of the holes move from the base into the collector of the transistor, thus giving rise to a collector current I_c (see Fig. 33*b*). If all the holes injected by the emitter were to reach the collector, there would be no current at all in the base circuit. Actually, some of the holes diffusing through the base region recombine with the free electrons (majority carriers) in this region and produce a base current I_b. Therefore, the emitter current I_e is related to the collector and base currents as follows:

$$I_e = I_b + I_c \tag{1}$$

A figure of particular interest is the ratio of the change in current ΔI_c appearing at the collector output terminal to a given current change ΔI_e appearing at the emitter input terminal. This figure is called the *current amplification factor* or *current transfer ratio* of the transistor and is denoted by the Greek letter α. Expressing this mathematically, it may be written as

$$\alpha = \frac{\Delta I_c}{\Delta I_e} \text{ at } V_{c.b} = \text{const} \tag{2}$$

Usually α ranges from 0.95 to 0.99.

With the emitter reverse-biased or the emitter circuit being open, the collector passes a current $I_{c.rev}$ known as the collector *reverse* (or zero) current. The value of the

collector reverse current depends on the concentration of minority carriers in the semiconductor.

With $I_{c.rev}$ taken into account, the collector current will be

$$I_c = I_{c.rev} + \alpha I_e$$

Basic transistor circuits. Since α has a value close to unity, it may be considered in accordance with equation (2) that the collector current increases approximately by the same number of times as the emitter current. This circumstance allows transistors to be used as amplifiers.

The amplifying characteristics of transistors are specified by their *power*, *current**, and *voltage gain* denoted by the letters G, H, and A, respectively.

The power gain is given by

$$G = \frac{P_l}{P_{in}}$$

where P_l =load power consumption
P_{in} =transistor power input

The load power consumption equals:

$$P_l = I_l^2 R_l = \frac{V_l^2}{R_l}$$

and the transistor power input is:

$$P_{in} = I_{in}^2 R_{in} = \frac{V_{in}^2}{R_{in}}$$

where I_l, V_l, I_{in}, and V_{in} = r.m.s. values of the currents and voltages involved
R_l =load resistance
R_{in} =transistor input resistance

Hence,

$$G = \left(\frac{I_l}{I_{in}}\right)^2 \frac{R_l}{R_{in}} = \left(\frac{V_l}{V_{in}}\right)^2 \frac{R_{in}}{R_l} \qquad (3)$$

* A distinction is made between the *current amplification factor* α and the *current gain* H of a transistor. The former is a property of the given transistor; the latter is influenced by the external circuitry connected to the transistor.

The parenthesized terms of the above equation represent, respectively:

the current gain

$$H = \frac{I_l}{I_{in}} \tag{4}$$

and the voltage gain

$$A = \frac{V_l}{V_{in}} \tag{5}$$

Equations (3), (4), and (5) are to be taken into account when selecting transistors for a given application.

Transistors may have a common-base, common-emitter or common-collector circuit configuration. In all these circuits one terminal is common to both input and output. The circuit configurations are illustrated in Fig. 34 where the input voltage is shown to be at the left- and the output voltage at the right-hand side of the circuit.

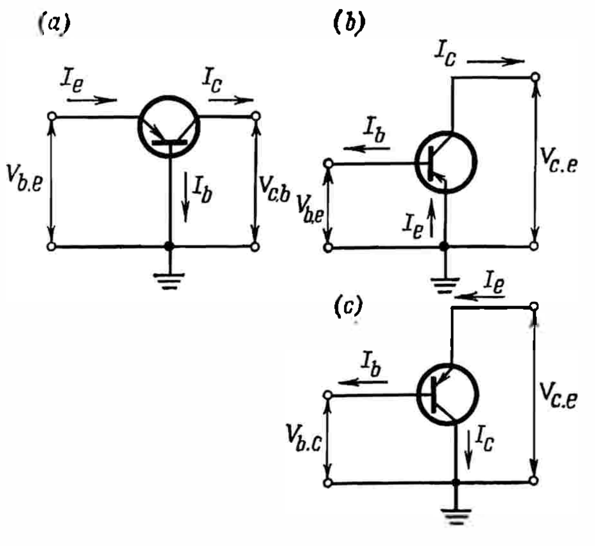


Fig. 34. Transistor connections
(a) common base; (b) common emitter; (c) common collecto r

The common-base circuit provides for the most stable operation as a power amplifier since the performance is hardly affected by changes in transistor parameters and their spread between individual transistors. The current gain is less and the voltage gain is greater than unity. The input voltage is in phase with the output voltage of the circuit. Individual amplifier stages are to be transformer-coupled in view of the considerable difference between the input and output resistances of the circuit.

The common-emitter circuit offers a greater power gain and is the most widely used even though its stability of operation is poorer than that of the common-base circuit. The current gain is greatly above unity, while the voltage gain is practically about the same as that of the common-base circuit. The output and input voltages are phase displaced by 180°. The input and output resistances in this case provide for easy matching of different power-amplifier stages.

The common-collector circuit has approximately the same current gain stability as the common-emitter circuit. The voltage gain is close to unity, while the output and input voltages are in phase. Common-collector circuits are employed in cases where high input resistance is essential.

The more important relative characteristics of transistor circuits may be summarized as follows:

	Current gain	Power gain	Input impedance	Output impedance
Common base	Low*	Interme-diate	Lowest	Highest
Common emitter	High	Highest	Interme-diate	Interme-diate
Common collector	High	Lowest	Highest	Lowest

* Normally below unity.

Transistor volt-ampere characteristics. By analogy with the semiconductor diode, the relationship between the parameters of a transistor is described by its volt-ampere characteristics. As in the case of vacuum-tube triodes, these

characteristics are non-linear and, therefore, the parameters of the transistor depend largely on the point of the characteristic curve at which it is actually operating.

The state of a transistor is determined by four variable quantities and, consequently, can be fully described by two sets of static characteristics representing the interrelation between three quantities. For the sake of convenience, the voltage is taken to be the independent variable of these functions. This makes it possible to use the same terminology and methods of calculation as in the case of vacuum-tube circuits. As a rule, reference handbooks and manuals give the volt-ampere characteristics of common-base and common-emitter transistors.

For example, the volt-ampere characteristics of a common-emitter transistor are fully described by the following set of equations:

$$I_b = f(V_{b.e}) \text{ at } V_{c.e} = \text{const}$$
$$I_c = f\ (V_{c.e}) \text{ at } V_b = \text{const}$$

where $V_{b.e}$ = voltage across the base and emitter
$V_{c.e}$ = voltage across the collector and emitter

The first characteristic is called the input characteristic, and the second one is known as the output characteristic of the transistor.

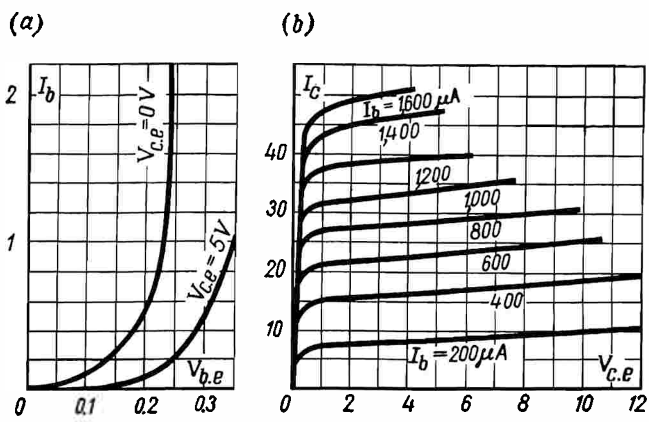


Fig. 35. Transistor volt-ampere characteristics
(a) input; (b) output

When the collector-emitter voltage $V_{c.e}=0$, the input characteristic of the transistor is exactly the same as the forward characteristic of an ordinary diode: with the base-emitter voltage $V_{b.e}=0$, the base current $I_b=0$ (Fig. 35*a*). As the collector-emitter voltage $V_{c.e}$ increases above zero, the input characteristic curve is seen to be shifted to the right from the $V_{c.e}=0$ curve. This means that the base current I_b decreases with increasing collector-emitter voltage $V_{c.e}$ and constant base-emitter voltage $V_{b.e}$. The collector junction field set up by the collector-emitter voltage $V_{c.e}$ accelerates the diffusion of charge carriers from the base into the collector. Therefore, they are less likely to recombine within the base region and the base current will be correspondingly smaller.

Figure 35*b* shows a set of output characteristic curves for different values of the base current I_b. With the collector current I_c equal to zero, the collector-emitter voltage $V_{c.e}$ is also zero for all the characteristic curves. In the absence of a collector junction field, all the charge carriers recombine within the base region and no current flows through the collector junction. As the voltage applied to the collector increases, it is seen that the collector current begins to rise sharply and then remains practically constant at a value determined mainly by the magnitude of the base current, i.e.,

$$I_c = \beta I_b \text{ at } V_{c.e} = \text{const}$$

where $V_{c.e}$ =voltage across the emitter and collector
β =current amplification factor for the common-emitter transistor

Factor β is much greater than unity and its approximate value can be found from the following equation:

$$\beta \approx \frac{\alpha}{1-\alpha}$$

As may be seen from the set of characteristic curves shown in Fig. 35*b*, the curves are shifted upwards with increasing base current I_b, i.e., the collector current I_c increases with increasing base current I_b and constant collector-emitter voltage $V_{c.e}$. The base current I_b will be the greater, the higher the voltage $V_{b.e}$ applied to the base

and emitter (Fig. 35*a*). The same rise of base-emitter voltage $V_{b.e}$ causes a corresponding increase in the current due to the passage of charge carriers through the emitter junction and, consequently, leads to an increase in the current flowing through the collector junction.

It should be noted that the curves of Fig. 35*b* are unequally spaced vertically although they are plotted for equal increments of 200 microamperes in the base current I_b. This is due to the fact that the current amplification factor α varies with the emitter current in accordance with equations (1) and (2).

Transistor temperature characteristics. The temperature of *p-n* junctions rises not only with ambient temperature but also as a result of power dissipation during operation. High temperature rises have a marked effect on the parameters of transistors. Thus, the concentration of minority carriers is known to increase with rising temperature. The higher the temperature, the greater the number of electron-hole pairs and, consequently, the higher the concentration of minority carriers in the semiconductor material. This, in turn increases the reverse current of the transistor as the internal field of the *p-n* junctions accelerates the movement of minority carriers. For example, the collector reverse current of silicon transistors is liable to increase 2.5 times at a temperature rise of 10°C. The current amplification factor β is subject to a multi-fold increase over the range of operating temperatures of the transistor. The transistor input and output characteristics change accordingly with varying temperature.

The reliability of measuring instruments and other electrical equipment employing transistors operating within a wide range of temperatures is improved by resorting to various methods of temperature compensation. Basically, these methods are aimed at maintaining the operation of the transistor automatically at a specified point of its characteristic curve. This is achieved by controlling the operating conditions of the transistor with the aid of temperature-compensating elements (diodes and thermosensitive resistors) or by providing for negative feedback.

Transistor design. Transistors differ in construction according to their power rating and the method of product-

ion of the *p-n* junction. They are usually enclosed in a hermetically-sealed cylindrical metal case with the terminals brought out at one end of the case (see Fig. 32). A typical low-power junction transistor is shown in Fig. 36.

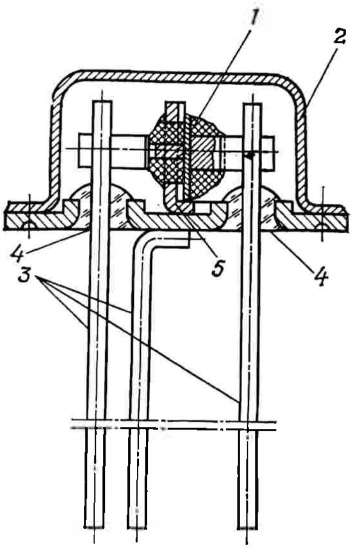


Fig. 36. Typical construction of low-power junction transistor

1—germanium crystal with *p-n* junctions; *2*— case; *3*— terminals; *4*—insulator; *5*—crystal support

The code markings are made on the case of the transistor and indicate the manufacturer's trade mark, the type of the given transistor, and the month and year of its manufacture.

Transistor applications. Transistors are of practically unlimited application. They have found widespread use as low- and high-frequency amplifiers, oscillators, voltage limiters, pulse shapers, switching elements in logical circuits and analogue computers, etc.

A detailed account of various circuits employing transistors will be given in Chapter Five.

3.4. Photodiodes, Phototransistors, Photoresistors, Phosphide Diodes, and Laser Diodes

Among the most promising devices for conversion of light into electrical energy and vice versa are such semiconductor transducers as photodiodes, phototransistors, photoresistors, phosphide diodes, and laser diodes. These transducers offer all the well-known advantages of semiconductor devices (small weight and size, long life-time, low power consumption) over vacuum valves and are of higher sensitivity than the latter.

Photodiodes. These semiconductor diodes rely for their operation on the dependence of the reverse current on the intensity of light that strikes the *p-n* junction of the diode. The reverse current is for all practical purposes independent of the reverse voltage applied to the diode and increases with the intensity of light falling on the barrier layer of the junction, this effect being due to the accompanying increase in the number of minority carriers.

The sensitivity of photodiodes to light is determined by the ratio of the resultant change in reverse current to the change in the luminous flux striking the barrier layer. Generally, silicon and germanium photodiodes have a sensitivity of about 10 to 20 milliamperes per lumen.

A typical photodiode is shown in Fig. 37. The diode is built so that one side of the *p-n* junction faces a glass window through which the light is passed, while other sides of the junction are shut off from light.

Photodiodes are used as light-sensitive elements for the conversion of optical values (surface illumination, flame temperature, etc.) into electrical quantities that can be measured by appropriate electrical measuring instruments.

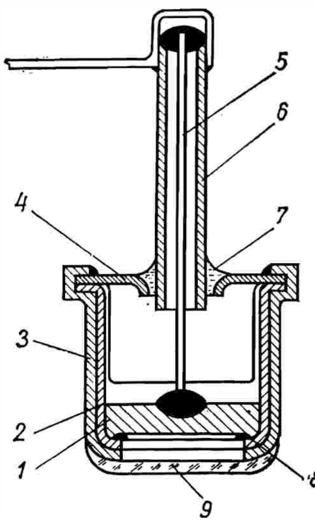


Fig. 37. Typical construction of photodiode

1 — germanium crystal with *p-n* junction; *2* — crystal support; *3* — metal case; *4* — ring; *5* — terminal; *6* — metal tube; *7* — glass insulator; *8* — tin ring; *9* — glass window

These diodes are often used under valve duty conditions of operation in various automatic control circuits (for signalling displacements, measuring speed of rotation, counting moving objects, etc.).

Phototransistors. These may be regarded as transistors in which the collector current depends on the intensity of light falling on the emitter junction. The collector cur-

rent of a phototransistor may be controlled according to requirements in exactly the same way as that of an ordinary transistor.

Common-emitter phototransistors have a sensitivity of 0.25 to 0.5 ampere per lumen, and a d.c. amplification factor ranging from 10 to 20.

Photoresistors (*photovaristors*). These incorporate a slab or film of semiconductor material that exhibits a change in its resistance when struck by light. The light-sensitive element is, as a rule, made of an n-type (electron conductivity) semiconductor. The incoming radiation imparts an additional amount of energy to the free electrons, thereby increasing the concentration of majority carriers in the semiconductor and, consequently, the conductivity of the photoresistor.

With no light falling on the semiconductor, a steady so-called *dark current* I_d flows through the closed circuit containing the photoresistor. Upon exposure to light, the photoresistor passes a greater current I_l. The difference between these currents is the signal output current corresponding to the given conditions of illumination:

$$I_s = I_l - I_d$$

Photoresistors possess a slower transient recovery than photodiodes and phototransistors, but exhibit a much longer life-time.

With the exception of applications requiring high-speed operation, photoresistors can be used in the same circuits and for the same purposes as photodiodes and phototransistors.

Phosphide diodes. Electric signals are converted into light by use of phosphide and laser diodes.

When pulses of excitation current I_{ex} are passed through the p-n junction of a phosphide diode (I_{ex}=10-30 milliamperes; V_{ex}=2-5 volts), pulses of light are emitted by the diode. The conversion of electric pulses into light takes place in an infinitely small time comparable to the time of propagation of light. Therefore, phosphide diodes may be considered as being practically inertialess. Depending on the relative content of impurities in the boundary regions of the p-n junction, phosphide diodes produce a red, yellow, or green glow.

Laser diodes. The main component of semiconductor laser diodes is a 0.4×0.4×0.1-mm gallium arsenide crystal with a *p-n* junction exhibiting a volt-ampere characteristic similar to that of an ordinary diode. The free electrons of the laser diode are excited by a current passed for this purpose through the *p-n* junction. At a definite value of the current, the laser begins to emit coherent light of very high intensity*. The current initiating and maintaining this emission of light is called the pumping current of the diode. The main advantages that semiconductors have over rubin and gas lasers are small weight and size, as well as high efficiency of operation.

The semiconductor laser should be kept at a very low temperature for normal operation. This requirement is met by placing it in a Dewar flask filled with liquid nitrogen. The pumping current of a laser with a gallium arsenide crystal ranges from 10 to 200 amperes at a duration of the current pulses of 0.1 to 1 microsecond. The emitted light has a wavelength of 8,430 ångströms and a spectral bandwidth of 30 to 50 ångströms (one ångström is equal to 10^{-7} mm). Laser diodes are used for optical communication, in laser radar altimeters, range finders, and other applications.

REVIEW QUESTIONS

3.1. What is a semiconductor device?
3.2. Explain the nature of the conductivity of semiconductor materials. Give the two types of conductivity.
3.3. What is meant by an *electron-hole junction?*
3.4. Explain the mechanism of current flow through a *p-n* junction.
3.5. How are semiconductor devices classified?
3.6. What is a *semiconductor diode?* Plot the volt-ampere characteristic of such a diode.
3.7. Give the main types of semiconductor diodes.
3.8. What is a *transistor?*
3.9. Explain the operation of a transistor and plot its volt-ampere characteristics.
3.10. Describe the relationship existing between the base, collector, and emitter currents of a transistor.
3.11. Draw the basic circuits of a transistor.
3.12. Explain the operation of photodiodes, phototransistors, photoresistors, phosphide diodes, and laser diodes.
3.13. Give some applications of semiconductor diodes and transistors.

* The word *laser* is an acronym for *Light Amplification by Stimulated Emission of Radiation.*

CHAPTER FOUR

Semiconductor Technology

4.1. Technological Cycle

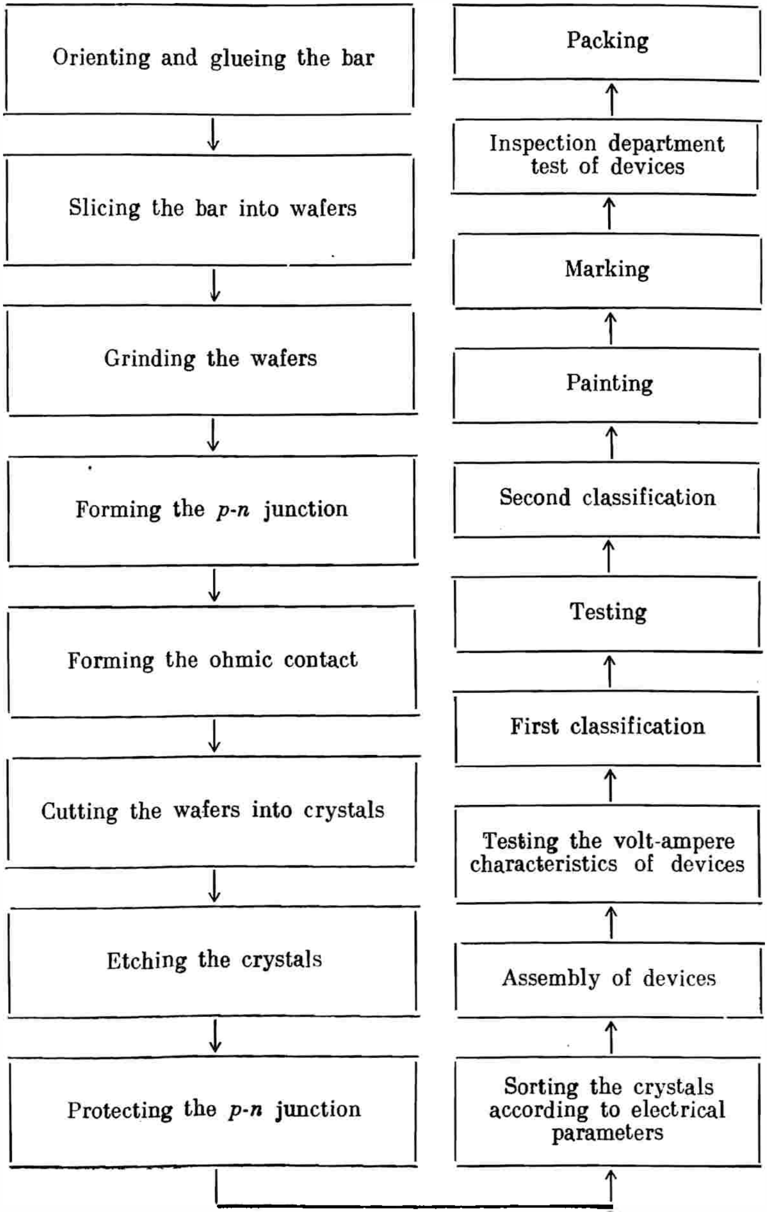
The technological cycle of semiconductor fabrication is a rather complex process entailing a great number of various operations. The necessity of fulfilment of individual operations and the order in which these operations are to be carried out depend largely on the type of the semiconductor device put into production and the technological policy adopted by the manufacturer.

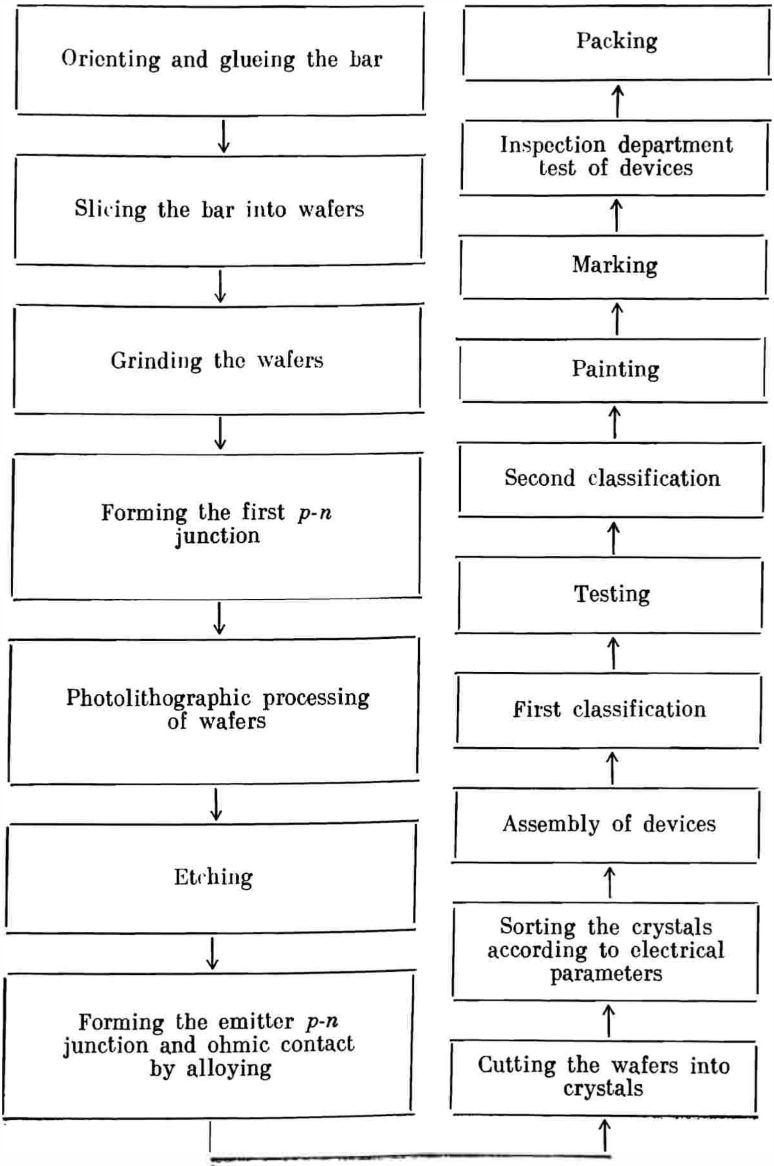
The main operations involved in the manufacture of diffused rectifier diodes and high-frequency diffused-alloy transistors are indicated in the diagrams presented on pages 69 and 70, respectively. These operations are as follows.

Orienting and glueing the bar. Silicon and germanium are produced in the form of bars, or ingots, 20 to 50 mm in diameter and 70 to 140 mm long. The crystal lattice of such a bar is regularly spaced and oriented with respect to the bar face plane. Orientation of the bar amounts to establishing the direction of the crystal axis and the degree of its deviation from the bar face plane. This deviation should be within permissible limits, otherwise the operating parameters of the semiconductor device are liable to be impaired. Accurate orientation of the crystal axis is also essential for adequate reproducibility of these parameters.

The oriented bar is cemented to a special support on which it is sliced into wafers. In this way, proper orientation of the crystal axis with respect to the wafer face planes is ensured.

Slicing the bar into wafers. The bar glued to the support is sliced into wafers of required thickness (usually 0.15 to


Orienting and glueing the bar
Slicing the bar into wafers
Grinding the wafers
Forming the p-n junction
Forming the ohmic contact
Cutting the wafers into crystals
Etching the crystals
Protecting the p-n junction
Sorting the crystals according to electrical parameters
Assembly of devices
Testing the volt-ampere characteristics of devices
First classification
Testing
Second classification
Painting
Marking
Inspection department test of devices
Packing



Orienting and glueing the bar
Slicing the bar into wafers
Grinding the wafers
Forming the first p-n junction
Photolithographic processing of wafers
Etching
Forming the emitter p-n junction and ohmic contact by alloying
Cutting the wafers into crystals
Sorting the crystals according to electrical parameters
Assembly of devices
First classification
Testing
Second classification
Painting
Marking
Inspection department test of devices
Packing

1.0 mm). These wafers serve as the substrates on which the *p-n* junctions are subsequently formed.

Grinding the wafers. This operation is carried out to ensure that the wafers be of specified thickness throughout their full length. It provides, furthermore, a smooth surface, eliminating grooves and other surface irregularities appearing in the course of the preceding operation.

Forming the p-n junction. The basic element of any semiconductor device, the *p-n* junction, is formed on the surface of the semiconducting wafer by special processing.

Photolithographic processing. This operation is carried out to obtain separate sections of *p-n* junctions on a common substrate; it can also serve to obtain multilayer structures by etching away part of the semiconductor material.

Forming the ohmic (galvanic) contact. These contacts serve for holding the device terminal leads and connecting them to the *p-n* junction. These contacts should not exhibit any rectifying effects, i.e., they should not set up a flow of unidirectional current. Another requirement is that their ohmic resistance be as low as possible.

Cutting the wafers into crystals. The wafer is cut into separate crystals of required shape and size. The crystals are usually square or round and from fractions of a millimetre to several millimetres in size, depending on the type of device being manufactured.

The surface and side faces of the wafer or crystal are cleaned by etching; during this operation the thin film of oxides and impurities on the surface is removed. This operation is in certain cases also carried out to remove part of the semiconductor material after photolithographic processing.

After mechanical and chemical processing the wafers and crystals are washed and dried, if necessary, and then their appearance is checked.

Protecting the p-n junction. The side faces of the crystal with the open *p-n* junction are coated with a layer of special varnish to protect the junction against the effect of surrounding conditions. This operation ensures long-term stability of the electrical parameters of the *p-n* junction.

Sorting the crystals according to electrical parameters. During this process the main parameters of the crystals are

checked by measuring them. These parameters determine the quality of the semiconductor device in which the crystals are used. Individual crystals, that do not meet requirements, are rejected, and those complying with specifications are passed on to the following operations.

Assembly of the semiconductor devices involves various operations, such as soldering terminal leads to the contacts of the crystal, soldering the crystals to their supports (this being known as fabrication of subassemblies), coating the subassembly with a layer of protective varnish, sorting the subassemblies according to their electrical parameters, etc. The operations involved and the order in which they are carried out depend on the type of the device in question. The last operation is sealing the device, this being accomplished by welding (when the device is housed in a metal case) or soldering (in glass-encased devices). Other methods of sealing may also be employed. Sealing is necessary to protect the *p-n* junction from mechanical damage and ensure reliable operation of the device irrespective of surrounding conditions.

Classification of semiconductor devices. The device parameters are measured and the device is ascribed a certain type number of the given series according to the results of these measurements.

Testing. These tests include a series of measurements made to determine the quality of the semiconductor device in production. Some of the measurements are obligatory and are made on each device, whereas others are made only on samples taken from a batch.

Measurements and tests are discussed at length in Chapters Six and Eight.

Marking. The case of the semiconductor device should bear the type designation of the device, month and year of manufacture, and manufacturer's trade mark.

Inspection department tests. These tests are carried out according to a special schedule in order to make sure that the semiconductor device is in full compliance with specifications. These tests include mechanical and climatic tests.

Packing. Devices approved and passed by the inspection department and bearing its stamp are packed in boxes for delivery to users.

4.2. Basic Methods of *P-N* Junction Formation

P-n junctions are manufactured by various methods. Here we shall discuss the most widely used.

Forming alloyed or fused p-n junctions. To obtain a *p-n* junction two silicon wafers having opposite types of conductivity, *p*-type and *n*-type (Fig. 38), are separated by

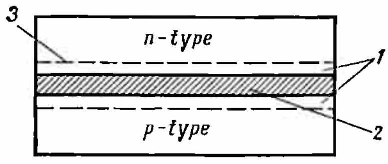


Fig. 38. Semiconductor structure with aluminium alloyed to silicon

1 — recrystallized layers; 2 — aluminium-silicon alloy (silumin); 3 — *p-n* junction

aluminium foil and baked in a vacuum furnace at a temperature of about 900°C. The rate of heating and cooling, as well as the time of exposure to high temperature depend on the type of device in which the junction is to be used.

In the course of exposure to high temperatures part of the silicon and aluminium dissolve and diffuse into each other melted. On cooling recrystallized silicon containing aluminium atoms (silumin) starts to crystallize out of the melt. Since aluminium acts as an acceptor in regard to silicon, the recrystallized silicon will exhibit hole-type conductivity. In this way two semiconductor materials with different types of conductivity are brought into contact, i.e., a *p-n* junction is formed. The *p*-type silicon serves for uniform melting of silicon into aluminium. Since silicon was present during the process of melting on either side of the aluminium foil, the recrystallized silicon will also appear on both sides of the metal. The thermal coefficient of linear expansion of recrystallized silicon is much closer to the coefficient of silicon than that of aluminium. This enables *p-n* junctions of considerable areas (needed for medium- and high-power devices) to be formed without cracks appearing in the crystal.

Forming diffused p-n junctions. The method used is based on the ability of atoms of one material to penetrate (diffuse) into another. Assuming that the concentration of impurity atoms on the surface of a semiconductor is C_1 (Fig. 39) and

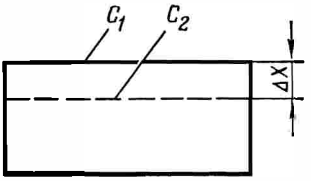


Fig. 39. Concentration of diffusing impurity

that it will be C_2 at a depth Δx below the surface (C_2 being lower than C_1), the difference in concentrations will cause the impurity atoms to diffuse into the semiconductor material. The rate of diffusion is a function of the temperature and the nature of the impurity.

The conductivity type of a semiconductor can be altered by adding a properly selected doping impurity. At a certain depth the concentration of doping impurity and that of the initial material become equal to one another and no diffusion takes place.

Depending on the way in which the doping impurity is added three types of diffusion are distinguished:

diffusion from a gaseous phase;
diffusion from a surface liquid phase;
diffusion from a solid phase.

(Here phase means the state of the medium.)

Diffusion from a gaseous phase. If a semiconductor wafer is placed together with a small piece of doping material inside a closed volume and both are heated to a certain temperature, the doping material will (under certain conditions) sublimate from the solid phase directly into the gaseous phase and a certain pressure of the doping element vapours will be established inside the given volume. The molecules of the vapour will be adsorbed by the surfaces of the semiconductor wafer. At a sufficiently high temperature the adsorbed molecules will diffuse into the bulk of the semiconductor wafer.

Diffusion from a surface liquid phase. In this case diffusion takes place at high temperatures from a layer of the doping material deposited onto the surface of the semiconductor wafer. It is considered that the doping material first changes to the liquid phase (melts) and then in-

teracts with the semiconductor material. This method is used, for instance, to diffuse aluminium, indium, and gallium doping impurities, deposited onto a semiconductor wafer by evaporation under vacuum.

Diffusion from a solid phase. This type of diffusion is used to transfer the atoms of a doping impurity from the solid solution in one region of the semiconductor material into an adjacent region of the same semiconductor, in which there are no impurities of this kind.

The advantages of diffusion over alloying may be summarized as follows:

possibility of controlling the difference in concentrations of the doping impurity according to the specified breakdown voltage of the junction (different breakdown voltages can be obtained by varying the concentration in semiconductor materials of one and the same resistivity);

elimination of structural flaws within the area of *p-n* junction formation;

formation of *p-n* junctions at greater depths below the surface of the wafer. This allows a base layer less than 100 microns thick to be obtained in wafers of considerable thickness;

easy control and good reproducibility of results, since the diffusion process is of sufficiently long duration.

Diffusion technique, however, has the following drawbacks:

difficulty of junction formation due to comparatively high temperatures involved, probability of changes in the resistivity of silicon, and even the type of conductivity of germanium;

difficulty of making ohmic contacts.

Growing a semiconductor junction out of a melt. This method makes it possible to obtain *p-n* junctions with a high breakdown voltage directly within the crystal bar. The method consists in pulling a new semiconductor bar out of a melted semiconductor material by means of a special rotating primer in an atmosphere of inert gases, the *p-n* junction being formed during the growth of the crystal in the following way.

A monocrystal (i.e., a crystal with a lattice structure in which the atoms or molecules are arranged in an orderly

manner throughout its volume) is pulled out of a melt of a *p*-type semiconductor of high resistivity. A doping impurity of *n*-type conductivity is added to the melt; the impurity is added in such an amount as to change the type of conductivity of the growing crystal and make this conductivity as high as possible. The process is discontinued as soon as the crystal becomes of required size. Growing a semiconductor junction out of a melt is a comparatively simple process and may be employed to form several *p-n* junctions in a single crystal.

Formation of semiconductor junctions by this method presents certain difficulties since extremely pure initial materials (silicon) are needed. Furthermore, to obtain a thickness of the crystal of about 200 to 400 microns, all the rest of the material is to be removed by grinding which is also rather difficult due to the curvature of the *p-n* junction formed by growing (Fig. 40).

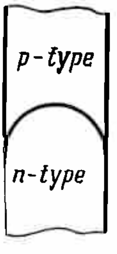


Fig. 40. Grown *p-n* junction

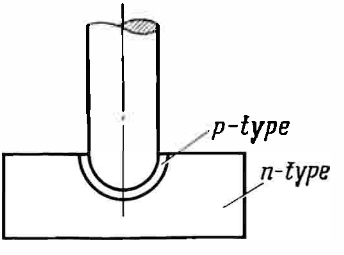


Fig. 41. *P-n* junction formed by the point-contact method

Point-contact junction formation. This technique is resorted to in manufacturing point-contact semiconductor devices.

According to this method an indium-coated bronze electrode with a sharp tip is brought into contact with the polished and etched surface of a germanium crystal of *n*-type conductivity. In this position the electrode is fastened securely and the contact is processed by passing a heavy current pulse (2 to 3 amperes of 0.08 to 0.1 second duration) through it; this process is known as electric forming. Since the contact area is very small and the current

density is, consequently, very high, a temperature high enough to melt the electrode material is developed at the point of contact. The indium coating diffuses into the germanium crystal producing a region of *p*-type conductivity owing to the fact that indium acts as an acceptor (Fig. 41). As a result, a *p-n* junction is formed at the boundary between this region and the initial germanium crystal.

The main advantage of this method lies in that quite simple equipment is used and, as a result, the cost of manufacture is substantially reduced.

Among its drawbacks the following should be mentioned:

low mechanical strength of the semiconductor junction;

considerable dependence of the junction parameters on the state of the crystal surface and the contact electrode, as well as on the pressure of the electrode;

considerable instability of electrical parameters;

significant spread of the semiconductor device parameters.

Electrochemical method. This method is used mainly in the formation of *p-n* junctions for high-frequency transistors due to the possibility of obtaining extremely small spacings between the emitter and collector (as small as 4 microns). In contrast to other methods of *p-n* junction formation, where the junction is formed by adding various doping impurities, the hole-conductivity region of these transistors is produced by physical methods, i.e., by eliminating electrons from the surface layer and obtaining a predominantly hole-type conductivity within this region.

This is achieved by etching a crater in the semiconductor crystal and depositing metal into it. The most suitable metals for this purpose are indium, zinc, cadmium, tin, and copper.

The advantages of this method are:

formation of semiconductor devices with extremely small spacings between the emitter and collector, thus improving the high-frequency performance, i.e., the limiting frequency of the triode;

easy automatic processing.

The main disadvantages are:

lower emitter efficiency as compared to junctions formed by the alloying method, this impairing the amplifying characteristics of the device;

high base resistance due to the extremely small dimensions of the base region, this deteriorating the maximum oscillation frequency;

difficulty in producing large electrode areas, this limiting the power handling capacity of the devices manufactured to several score milliwatts.

4.3. Equipment for *P-N* Junction Fabrication

To form a diffused *p-n* junction the doping material should be deposited by some means onto the surface of the semiconductor. Deposition at high temperatures by evaporation under vacuum is the most commonly used method.

The installation used for evaporation consists of a vacuum system with a heater for preliminary heating the semiconductor surface prior to deposition and an evaporator for producing the doping material vapours. The heater is a graphite plate mounted rigidly on two bronze current-carrying supports. The semiconductor wafers to be coated with the doping agent are placed onto the heater operating at temperatures from 600 to 900°C.

The evaporator is arranged above the heater and consists of several parallel tungsten helixes held in place by current-carrying bars. Strips of thin metal foil of the required doping material are hung onto the helixes; due to the combined effect of high vacuum and temperature the foil melts and evaporates, spraying the material in all directions. As a result, atoms of the doping material are deposited onto the crystal surface and form a thin uniform coating. The range of temperatures at which evaporation of metals takes place is from several hundred to several thousand degrees Centigrade.

The evaporator and heater are supplied from separate power sources whose output currents can be controlled within a wide range.

The heater temperature (and, consequently, the temperature of the semiconductor wafers) is continuously controlled and maintained automatically at a constant level. The same is done as regards the degree of vacuum inside the installation. The general view of this installation can be seen in Fig. 42.

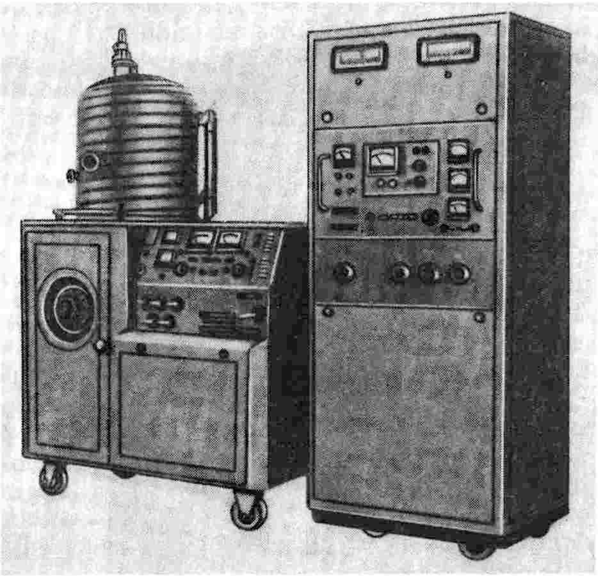


Fig. 42. Equipment for vacuum deposition of metals

Diffused and alloyed semiconductor junctions are formed in furnaces of different types equipped with heating elements for maintaining temperatures up to 900-1,200°C. The heat system in one of these furnaces comprises two concentric pipes about 650 mm long and 42 and 60 mm in diameter, respectively. The pipes are welded at one end and the opposite ends are insulated from each other by ceramic spacers and connected to current-carrying busbars. This heater draws a current up to 1,400 amperes supplied at a voltage of 7 volts.

The heating elements may also be made of tungsten or special materials, such as silit (a heat-resistant material composed of SiC powder mixed with a silicon binder); induction heating by high-frequency currents is also practised.

Figure 43 gives the general view of a furnace with silit heating elements, used for thermo-diffusion processing.

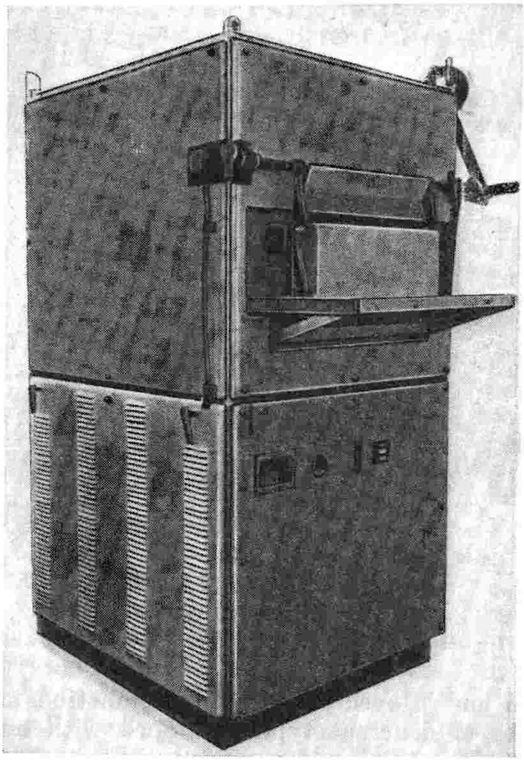


Fig. 43. Thermo-diffusion furnace with silit heating elements

Conveyer continuous-operation furnaces have found wide application. Such furnaces operate as follows.

The furnace has a directly-heated pipe of welded heat-resistant steel 28×34 mm in cross section containing several heating elements. The heating zone can be varied by 600 to 800 mm. The conveyer belt made of special steel or ferrochrome is passed continuously through the furnace at a speed of 5 to 150 mm per minute and carries the wafers placed in special containers.

The diffusion takes place in a gaseous atmosphere. The operating temperature is varied by varying the heating

element temperature and the rate of conveyer belt travel.

Point-contact junctions are formed with the aid of bench-mounted equipment consisting of a d.c. stabilized source of pulse current supply and an auxiliary mechanism that presses the contact electrode against the surface of the semiconductor crystal.

4.4. Photolithographic Processing

This process allows to form several individual *p-n* junctions on a common semiconductor substrate. This technique can also serve to obtain multilayer structures for transistors and controlled diodes. Several junctions on a common substrate and multilayer structures are obtained by etching away part of the semiconductor material in the desired pattern. Photolithographic processing provides a means of metallizing semiconductor wafers in any required pattern, and is also resorted to for local diffusion of doping impurities.

All the operations involved in photolithographic processing can be carried out with a high degree of accuracy and ensure adequate reproducibility (i.e., a low spread of the parameters of individual devices contained in a single lot). This method finds an ever widening field of application.

Figure 44 presents a cross-sectional view of semiconductor wafer *1* with region *2* etched away.

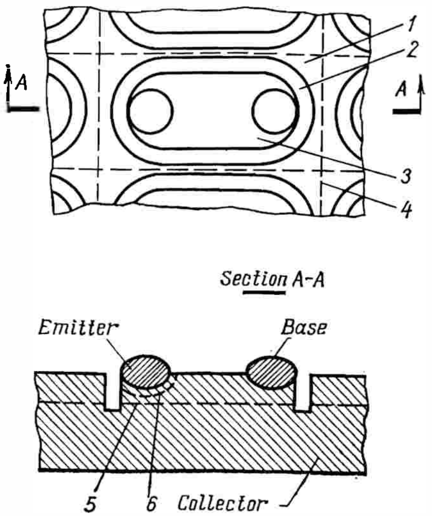


Fig. 44. Section of wafer with *p-n* junction after photolithographic processing

1—wafer; *2*—etched region; *3*—active region; *4*—line along which the wafer is cut; *5*—collector *p-n* junction; *6*—emitter *p-n* junction

If the wafer is then cut along lines *4* active region *3* containing collector junction *5* and emitter junction *6*, as well as the emitter and base contacts will be inside each crystal. The electrical parameters of each junction can be tested directly on the wafer, since individual crystals are insulated from one another.

By this method the wafer is first coated with a protective oxide film and then given a layer of emulsion sensitive to light. When exposed to light through a special mask, the exposed regions become insoluble, whereas the unexposed regions retain their solubility. After exposure the film is developed and the unexposed regions are dissolved, baring the underlying semiconductor surface. The wafer is then fixed in special solutions. After that the wafer is baked at a high temperature so as to polymerize the film and make it acid-resistant.

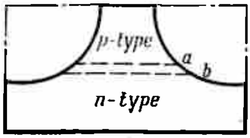
Wafers thus treated are ready for etching and metallizing. When etching only a part of the wafer surface (namely, that without the protective film coating) is processed. The depth of etching is controlled by varying the duration of this operation. After etching the protective film is removed from the surface of the wafer by special solvents.

4.5. Newly-Developed Methods of Semiconductor Production

New technological processes are finding ever increasing application in the production of semiconductor devices. Those by which mesa, planar, and epitaxially grown semiconductor devices are produced should be mentioned as the most promising.

Mesa-technology. As a general rule, crystals (i.e., structures with *p-n* junctions) are obtained in the form of parallelepipeds, cubes or cylinders with the *p-n* junction parallel to one of their planes and the dimensions of the junction equal to that of the crystal base. By this technological process the dimensions of the junction are reduced without changing the dimensions of the crystal base (Fig. 45). This is achieved by etching away part of the semiconductor material together with the *p-n* junction in

Fig. 45. Formation of mesa-structure



order to obtain a configuration known as a *mesa-structure* ('mesa' in Spanish means 'table', 'plateau'). The reduced dimensions of the *p-n* junction provide for a lower capacitance of the semiconductor device, enabling the operating frequency to be increased, while an extended section of the junction at the sides of the crystal (section *a-b* in Fig. 45) tends to improve the breakdown voltage.

Planar technology. This method is referred to as planar in view of the fact that the *p-n* junction of semiconductor devices (diodes, triodes) are formed only on one side of the semiconductor wafer. The wafer is first heat-treated in an oxidizing atmosphere to form a film of insulating oxides (SiO_2) about 1 to 1.5 microns thick on the wafer. After that a series of regions free of this protective film are obtained by photolithographic processing and selective etching. The base *p-n* junction is formed in these regions by diffusion. Then the emitter region is obtained in the same way by photolithographic processing, selective etching, and diffusion.

The main advantage of this method is that the base and emitter regions are protected at the points where they appear on the surface of the wafer by an oxide film. This film substantially lessens the effect of surrounding conditions, this providing for long-term stability of the electrical parameters and their reproducibility (i.e., reduces their spread). Stray currents are also minimized, thus improving the current gain of the semiconductor device.

Planar structures are formed on a common semiconductor wafer, after that the base and emitter leads are soldered and then the wafer is cut into individual crystals. The crystals are mounted into their cases in the usual way. The whole production process is thus considerably simplified.

Epitaxially grown junctions. By this method the *p-n* junction is formed by epitaxially growing semiconducting

films on a semiconducting substrate. The film grown in this manner is considered as epitaxial if the axis of its crystal lattice is in line with that of the substrate lattice.

For proper formation of the *p-n* junction the conductivity of the grown film should be opposite to that of the substrate.

This process permits thin-base devices to be fabricated, which is necessary in the manufacture of high-frequency transistors, high-speed pulse and switching diodes.

Epitaxially grown junctions may solve the problem of designing high-power and high-voltage devices. The contradictory requirements that are to be met in this case by the semiconductor material can be illustrated by the following example: in order to pass heavy currents the resistivity of the semiconductor material should be as low as possible, whereas, on the contrary, a high breakdown voltage can be obtained only by making the resistivity of the material as high as possible. Epitaxially grown films give an answer to this problem since double-layer structures can be produced on a semiconductor substrate of low resistivity. When such a structure is used in a diode, the voltage drop across the device in the forward (conducting) direction is determined mainly by the low resistivity of the semiconductor substrate, whereas the breakdown voltage will be high, since it is determined by the high resistivity of the grown film. A double-layer collector can also be obtained offering the same advantages, namely, a low forward voltage drop due to the low resistivity of the substrate and a high breakdown voltage due to the high resistivity of the epitaxial film.

The main difficulty lies in obtaining an epitaxial film capable of carrying heavy current. When this difficulty is overcome it will be possible to design high-frequency pulse semiconductor devices with high breakdown voltages.

At present epitaxial films are deposited from a gaseous or liquid phase. One of the methods used to deposit epitaxial films out of a gaseous phase is as follows.

A germanium substrate of hole-type conductivity is placed in the low-temperature zone (300 to 600°C) of a tubular furnace, while the source (germanium of electron-type conductivity) and iodine salt are placed in the high-tempe-

rature zone (500 to 700°C). The heated iodine sublimates and reacts with the germanium source producing GeI_2. The temperature gradient in the furnace causes the GeI_2 to move to the low-temperature zone and decompose. The germanium deposits on the furnace walls and on the substrate, forming an epitaxial film. Thus iodine serves as a carrier of the germanium.

Epitaxial growth from a liquid phase occurs, essentially, in exactly the same way. This method is used, for instance, to produce gallium arsenide tunnel diodes. The process also takes place in a tubular furnace. The source material, gallium arsenide, dissolves in melted tin, and acts as the carrier.

At a temperature of 640°C the furnace is tilted so that the melted tin covers the surface of the substrate. On cooling the gallium arsenide of the substrate dissolves until a state of equilibrium with the previously dissolved source material sets in. After that gallium arsenide is recovered out of the melt and epitaxial film growth takes place. In this case the melted tin serves not only as a solvent and carrier but, also, as a doping impurity with respect to gallium arsenide.

4.6. Selection of Technological Method

A characteristic feature of modern science and engineering is the ever increasing demand for semiconductor devices of higher quality and reliability. These demands can be met only by improving the technology of semiconductor production.

At present most transistors and semiconductor diodes have alloyed or fused *p-n* junctions. This technological process is well known and developed in great detail, providing the production of high-quality devices. Some manufacturers, however, consider this technology to be too costly since it involves considerable expenditure of semiconductor materials.

Use of diffused junctions instead of alloyed junctions allows the junction to be formed on a single wafer; this needs a smaller amount of semiconductor materials and improves the mechanical strength of the semiconductor device.

Furthermore, the process of diffusion can easily be automatically controlled. This, in turn, gives a smaller spread of the semiconductor device parameters since the accuracy of performance of diffusion operations determines the electrical characteristics of the finished product.

Point-contact junctions are suitable only for low-power diodes. Most of the operations involved in this production process can easily be automatically controlled. Due, however, to the drawbacks mentioned above, most low-power diodes are now manufactured with alloyed or diffused *p-n* junctions and mesa-structures.

High-frequency transistors are usually manufactured by a process combining both diffusion and alloying. In this case the emitter and collector junctions are diffused, while the base region is alloyed. This makes it possible to obtain devices with a limiting frequency of up to 1,000 megahertzes using simple and inexpensive equipment.

In planar semiconductor devices diffused *p-n* junctions are employed.

Forming *p-n* junctions by growth out of a melt and electrochemical processing are rarely resorted to because of the complexity of the technological equipment required and the difficulty of ensuring adequate automatic control of the operations involved.

Epitaxially grown semiconductor junctions are the best solution to most of these problems and here, obviously, lies the future of semiconductor device production. With this technology there is a great saving in semiconductor materials, the devices produced are of lower cost, smaller dimensions and faster response. Epitaxially grown semiconductor junctions are at present used in experimental and small-scale production of solid-state laser, phosphide, and tunnel diodes.

4.7. Formation of Ohmic Contacts

A reliable electrical contact must be established between the external leads of a semiconductor device and its active regions, such as the emitter, base, collector, and gate.

If a terminal lead is to be connected to a metal electrode formed on the semiconductor surface during previous ope-

rations, this may be easily done, for instance, by soldering.

In the case of a diffused semiconductor junction or one grown out of melt, as well as in junctions formed by certain other methods, there is no metal layer on the semiconductor surface and an additional operation is necessary to produce an ohmic contact. The word "ohmic" implies that this contact should not exhibit any rectifying properties and that the contact resistance should follow Ohm's law, i.e., the volt-ampere characteristic of the contact should be linear. Its resistance should be as low as possible to minimize power losses and ensure maximum efficiency.

Another requirement is that the contact material should not inject any minority charge carriers, since this will significantly worsen the performance of the semiconductor device. For instance, minority charge carriers reaching the *p-n* junction cause a considerable increase in the reverse current. Moreover, the ohmic contact should be of proper mechanical strength and high heat conductivity.

A metal layer deposited directly onto the crystal surface cannot possibly serve as an ohmic contact since the junction between the semiconductor and the deposited metal will form a barrier layer featuring a nonlinear characteristic. Therefore, the deposited metal is usually subjected to heat treatment in the result of which the semiconductor surface layer becomes enriched by the atoms of the given metal or an especially added element (due to formation of a recrystallized or diffused layer), thus changing the electrical parameters of the contact according to requirements.

Ohmic contacts can be obtained by several methods. The most widely used methods are: electrochemical deposition or metal spraying and, in certain cases, local metallization of the crystal surface.

Ohmic contacts are produced in the following way. A nickel layer is electrochemically deposited onto the surface of the wafer (or surface of the crystal as the case might be). Then the wafer is baked in an atmosphere of hydrogen at a temperature of 600 to 700°C for 5 to 10 minutes. During this process the nickel is fused into the wafer to a depth of several dozen microns and, finally, is tinned or plated with silver or gold.

A drop of solid tin attached to the end of a thin wire serves to deposit the tin. The wire eventually becomes the terminal lead of the semiconductor device. This operation is carried out at the melting point of tin.

Silver or gold plating is carried out in an electrolyte at a temperature of 20 to 60°C and a current density ranging from 1 to 1.5 amperes per square decimetre depending on the kind of metal used.

Metal spraying is carried out in much the same way as when forming a *p-n* junction. When local metallization is required all the rest of the wafer or crystal surface is given a protective coating applied, for instance, photolithographically.

4.8. Fabrication of Semiconductor Wafers and Crystals

Wafers are obtained by slicing semiconductor bars. The crystals, in turn, are obtained by cutting the wafers. Depending on the adopted method of fabrication, *p-n* junctions are formed on the wafer (which is then cut up into individual crystals) or are formed directly on the crystal. Sometimes, the crystals are grinded or polished, then etched, washed, dried, and after that the junction is given a protective coating of varnish. The crystals thus processed are fed to the device assembly line.

The wafers are cut into individual crystals by means of: (1) a diamond disc; (2) a hack saw; (3) a wire; (4) ultrasonic oscillations; (5) a diamond cutting tool; (6) abrasive powder streams; (7) chemical etching. The same is true for the operation of slicing semiconductor bars into wafers.

The best and most commonly used methods are cutting by ultrasound and with the aid of a diamond cutting tool.

Ultrasonic cutting is done on special lathes the cutting tool of which makes a progressively deepening groove in the semiconductor material. The tool support carries several dozen cutting tools so that the same number of crystals are cut at the same time.

The wafer is cut with a diamond cutting tool after the wafer has been photolithographically processed.

A special optical sighting device is used to ensure accurate orientation of the cutting tool. Such accuracy is essential since the *p-n* junction must be placed exactly at the centre of the crystal. This method is used in the manufacture of transistors and switching diodes.

After slicing a wafer it is necessary to grind its surface to obtain strictly parallel planes, ensure the required thickness, and remove all surface irregularities appearing on the surface after slicing.

Grinding is carried out on special lathes with the aid of an abrasive suspension (the abrasive grains being from 5 to 10 microns in size) in the following way. Suspension *4*

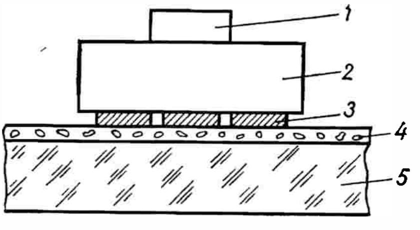


Fig. 46. Jig for grinding wafers

1—weight; *2*—special arbour; *3*—wafers; *4*—suspension; *5*—grinding wheel

(see Fig. 46) is poured onto glass grinding wheel *5*; wafers *3* are placed onto the grinding wheel and held in place with the aid of special arbour *2* and weight *1*.

Rotation of the grinding wheel or arbour causes the grains of the abrasive suspension to interact both with the wafer and the wheel. Glass being a more viscous material, the abrasive grains stick to the grinding wheel and grind the wafer surface.

The *p-n* junction is to be protected against the effect of surrounding conditions in order to ensure proper stability of the device parameters. This is done by various methods, the main being:

coating with varnish;

oxidization, i.e., forming a thin layer of silicon dioxide on the silicon surface;

silanation, i.e., providing a coating of silicon;

glazing with glass having a low melting point;

rendering the surface hydrophobic, i.e., treating in li-

quids or vapours that make the crystal surface water-repellent.

4.9. Assembly of Medium-Power Junction Diffusion Diodes

The process of assembly will be examined with reference to medium-power silicon diodes of the same series. All these diodes are of the same design (see Fig. 23*a*) and manufactured in exactly the same way, the difference being only in their electrical parameters.

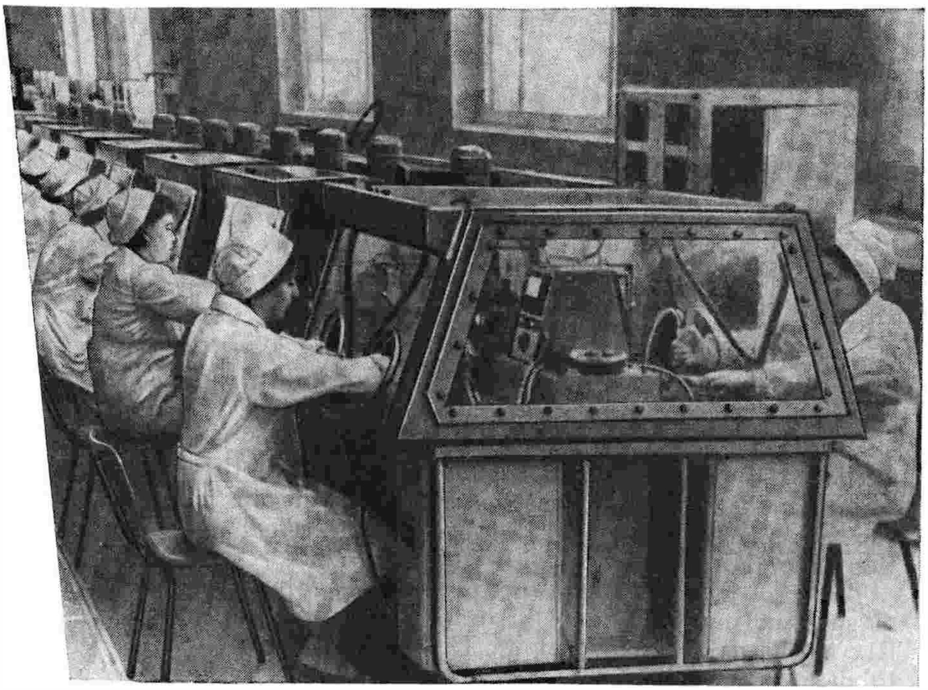


Fig. 47. Assembly line

All operations are carried out on an assembly line shown in Fig. 47. The diodes are assembled in special bench-mounted glove boxes (assembly chambers) at controlled tempera-

ture and humidity. The device being assembled is passed from one operator to another by a conveyer belt enclosed in a special duct linking the glove boxes of the assembly line.

Crystals with protective coatings are delivered to the assembly line, and subjected to the following operations.

Measurement of the reverse voltage of p-n junctions is the first operation to be carried out and is made with the aid of a semiautomatic device as follows. The crystals fitted into cells in a special container with the *p*-type conductivity side downwards are fed into the glove box. The crystals are taken out of their cells for measurements by means of a test probe with a vacuum sucker. Pressing a knob on the probe brings the latter into contact with the crystal, the magnitude of the reverse voltage is measured and one of two indicating lamps "reject" or "pass on" lights up. The crystals that have passed this test are returned to the container, whereas those that have not are rejected. The container is placed onto the conveyer belt and passed on to the next operator.

Preparation of crystals for soldering to supports. The crystal supports, washers, and leads are fed into the glove box beforehand. The container with crystals is dismantled and the crystals are transferred to another container. Here the components are stacked in the following order (from the bottom upwards): lead *8* (see Fig. 23*a*), solder washer *3*, silicon crystal *4* with the *p*-type conductivity side facing the bottom, solder washer *5*, and crystal support *7*. The filled container is closed with a lid that is securely fastened.

Soldering the p-n junctions. The container is fed into a hydrogen conveyer furnace. To this end the container is placed on the metal conveyer belt of the furnace and passed through it at a speed of 80 mm per minute. The temperature inside the furnace is kept within 300 to 320 °C limits and the solder washers are melted. At the furnace output the solder hardens and the *n*-type conductivity side of the crystal is firmly soldered to the crystal support, while the *p*-type conductivity side is soldered to the lead.

Emptying the container and checking the soldered joints. The container is taken off the furnace conveyer belt, placed on a metal slab inside the glove box and cooled for

about six to ten minutes. Then the container is dismantled with the aid of a pneumatic appliance and every crystal is taken out and inspected. The strength of attachment of the soldered joints is tested by means of a special gauge. Crystals meeting requirements are placed into another container, and all others are rejected.

Sorting the crystals according to the forward voltage drop and reverse current. Each crystal is taken out of the container and checked by a special semiautomatic tester which measures the forward voltage drop for a given reverse voltage. Crystals complying with specifications are passed to the next operation and all others are rejected.

Protecting the p-n junction and mounting-in the diode case. The crystal is coated with a thin layer of insulating vaseline (petroleum jelly) for protection against the influence of surrounding conditions. Then the crystal carried by a special container is fitted with case *1* and rigid lead *2* (Fig. 23*a*), care being taken to pass flexible lead *8* into the rigid one. After that the container is passed on to the next operator.

Pressure welding the diode case. Each assembled crystal is taken out of the container and placed onto the lower die of a press. Depression of a foot pedal brings the upper die down and the diode case is pressure welded.

Pinching off the rigid lead. The lead is passed into the aperture of a pneumatic press, thus actuating the press.

Welding the lead. This is done by spot welding. A special tool is used to pass a heavy current pulse of short duration through electrodes between which the leads are pressed by stepping on a foot pedal.

Punching a hole through the lead. This operation is performed outside the box since the diode has already been sealed. A hole is punched through the lead on a pneumatic punching press in much the same way as the rigid lead was pinched off.

4.10. Assembly of High-Frequency Diffusion-Alloy Transistors

This operation will be discussed with reference to high-frequency low-power germanium transistors. Such a transistor is shown in Fig. 48.

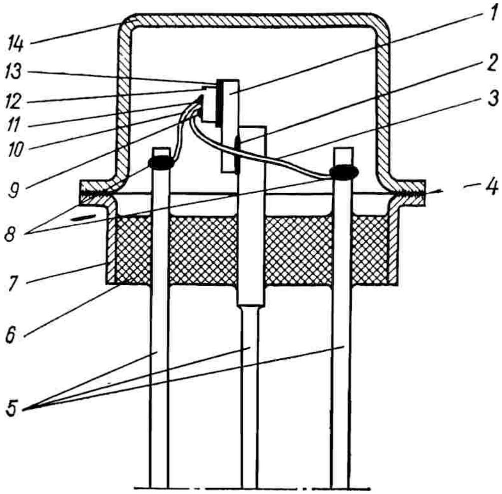


Fig. 48. Typical construction of high-frequency low-power transistor
1—crystal support; *2*, *8*—welds; *3*—emitter internal connection; *4*—welded seam; *5*—transistor terminals; *6*—insulator; *7*—stem; *9*—emitter contact; *10*—base connection; *11*—base contact; *12*—crystal; *13*—solder strip; *14*—case cap

The operations are made on an assembly line fed with crystals, base and emitter leads, crystal supports, case stems and caps from the auxiliary workshops of the plant.

Soldering the crystal to the support. Crystal *12* (Fig. 48) with its volt-ampere characteristic measured beforehand is fed into the glove box together with tinned crystal support *1*. The crystal is of a rectangular shape with sides about 1 mm long and the *p-n* junction at the centre of the crystal (see Fig. 44).

Two contact points, on the base and the emitter, are provided on the crystal.

The crystal support is placed into a metal container (Fig. 48), solder strip *13* is placed on top, and crystal *12* is mounted on top of the solder strip. This subassembly is fastened, placed on a conveyer belt, and delivered to a furnace where the soldering is performed.

Soldering the base and emitter leads. The crystal with its support is placed on a special heater with the longer side of the crystal horizontal. Pieces of gold-plated wire

terminated by a drop of tin are brought into contact first with the base, then with the emitter of the semiconductor device. After the drop melts, the heater power supply is cut off. After hardening the tin provides reliable connection of the base and emitter terminal leads.

Welding leads to the crystal support. Transistor stem 7 with the external leads is mounted in a jig on the welding apparatus. The crystal support is then fixed and welded by the usual method.

Soldering the electrode connections to the external leads. This is done in much the same way as the preceding operation.

Etching the subassembly. This is carried out in a mixture of several acids to remove all foreign matter that could have appeared on the subassembly surface due to welding. After etching, the subassembly is washed and dried.

First protective coating. The crystal is coated with a protective varnish, the points of welding being coated with a special glue. After coating the disassembly is cured in a special oven at a temperature of 80 to 100°C for two hours.

Second protective coating. This consists in coating the entire subassembly with vaseline.

Checking the maximum frequency of oscillation. Here a tentative test of the device quality is made. The subassembly is mounted on a suitable support and connected to the measuring circuit. Subassemblies with limiting frequencies below specified value are rejected, whereas those complying with requirements are passed on to the next operation.

Welding the case of the transistor. This final operation consists in welding together the two parts of the transistor case. This is done by pressing the cap to the stem and passing a current pulse through the assembly.

REVIEW QUESTIONS

4.1. Name the main operations carried out in manufacturing semiconductor devices.
4.2. By what methods are *p-n* junctions formed?
4.3. What technological equipment is used in forming *p-n* junctions?
4.4. Explain the principles of photolithography. What is achieved by this process?
4.5. Name some newly-developed methods of forming *p-n* junctions.
4.6. What is an ohmic contact and what is its purpose?

CHAPTER FIVE

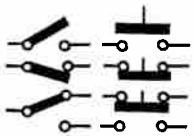
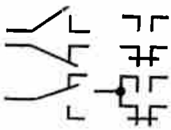
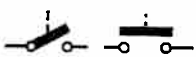
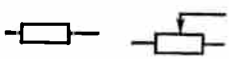
Electrical Measuring Circuits

5.1. Graphical Representation of Measuring Circuit Elements

The elements of measuring circuits used for testing and adjusting semiconductor devices should preferably be represented by the graphic symbols listed in Table 1.

Table 1

Graphical Symbols for Electrical and Electronics Diagrams

No.	Name	Symbol
1	Switch contacts: (a) normally open (b) normally closed (c) two-way	
2	Relay contacts: (a) normally open (b) normally closed (c) two-way	
3	Mechanically-operated contacts of pickups, sensing elements, limit switches, etc.	
4	Resistors	

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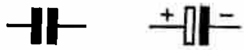
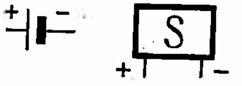
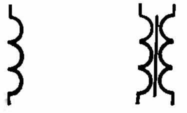
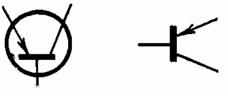
5	Capacitors	
6	Sources of supply	
7	Inductance coil, transformer	
8	Vacuum tube (triode)	
9	Type *p-n-p* transistor	
10	Diode	
11	Reference diode (voltage stabilizing tube)	
12	Switching diode	
13	Tunnel diode	
14	Photodiode	
15	Laser diode	

5.2. Rectifiers

Accessory equipment used for making electrical measurements, as well as testing and adjusting semiconductor devices, employs a wide variety of standard circuit elements, such as rectifiers, multivibrators, flip-flop elements, amplifiers, comparators, logical elements, filters, voltage stabilizers, triggers, etc. These circuit elements may be vacuum tubes, gas-filled tubes, voltage-stabilizing tubes, semiconductor devices, etc. Emphasis will be placed on semiconductor devices, these being the most promising for such applications owing to their low power consumption, small size, high efficiency, and reliability.

As a general rule, measuring circuits are supplied from a.c. mains through a power transformer provided with means for conversion of alternating current to direct current (rectification) and voltage stabilization. Only in exceptional cases may the measuring circuits be connected to supply from dry batteries and standard cells.

Rectification is usually effected by vacuum tubes and germanium or silicon diodes. Figure 49 shows some of the basic rectifier circuits used in joint with measuring instruments.

The most simple is the *single-phase half-wave circuit* of Fig. 49*a*. This circuit is used in cases where extensive rippling of the output current is of no consequence, and the load draws not more than 5 to 8 watts from the source of power supply.

Figures 49*b* and *c* illustrate different versions of *single-phase full-wave circuits* by means of which the currents of both half cycles are rectified and passed through the load.

Voltage doubling and *multiplying rectifier circuits* (Figs 49*d* and *e*) are made up of low-voltage circuit elements (diodes, capacitors) and produce a high output voltage. These circuits are employed when there is no need of currents above 3 to 50 milliamperes.

Heavier currents are handled by the *multiphase rectifier circuits* shown in Fig. 50. These circuits contain a capa-

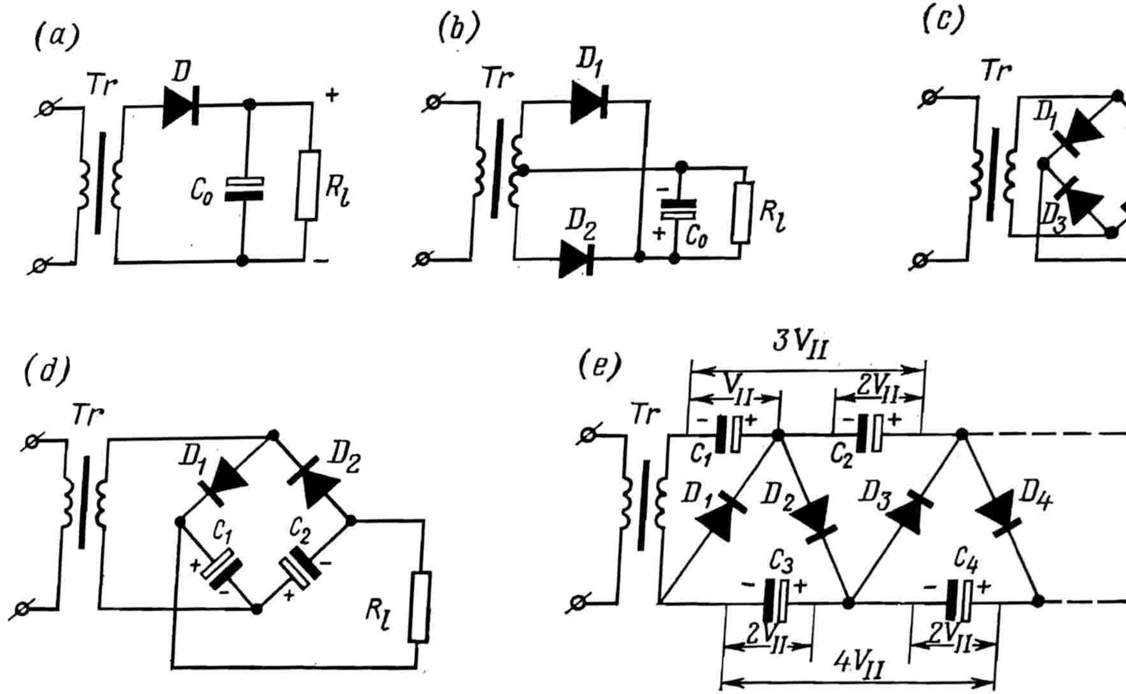


Fig. 49. Single-phase rectifier circuits

(*a*) half-wave rectifier; (*b*) and (*c*) full-wave rectifiers; (*d*) voltage-doubling rectifier; (*e*) voltage-multiplier rectifier; C_1-C_4—capacitors; R_l—load resistance; C_0—filter capacitor

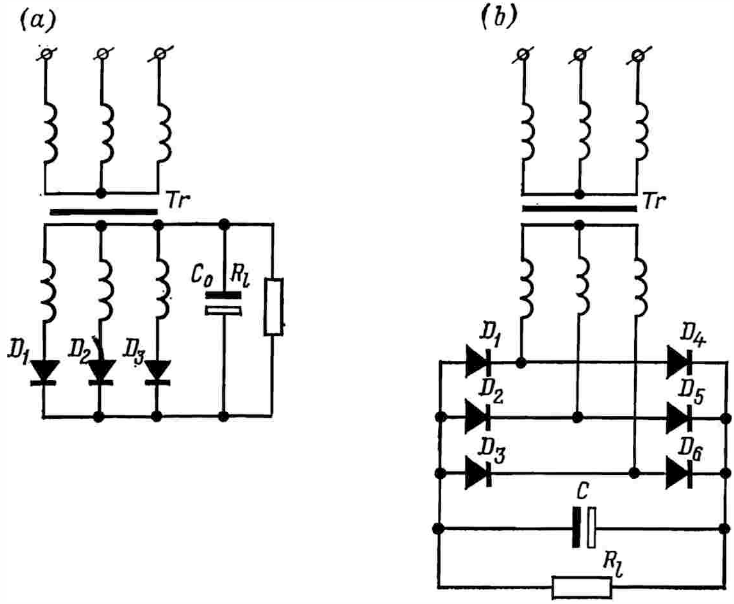


Fig. 50. Three-phase rectifier circuits
(a) **half-wave rectifier;** *(b)* **full-wave bridge rectifier**

citor C_0 that is connected across the d.c. side of the circuit so as to attenuate the ripple in the rectified output to the point where it is not objectionable.

The most commonly used for rectification is the *single-phase full-wave bridge circuit* (Figs 49*c* and 51). This rectifier circuit is built up of diodes D_1, D_2, D_3, D_4, and capacitor C_0.

During the first half cycle t_1, the sinusoidal current flows through the secondary winding of transformer *Tr*, diode D_1, load R_l, capacitor C_0, and further on through diode D_4.

In the course of the second half cycle t_2, the current path is through the transformer secondary winding, diode D_3, load R_l, capacitor C_0, and diode D_2. As a result, the current is passed unidirectionally through the load during both half cycles of the a.c. current.

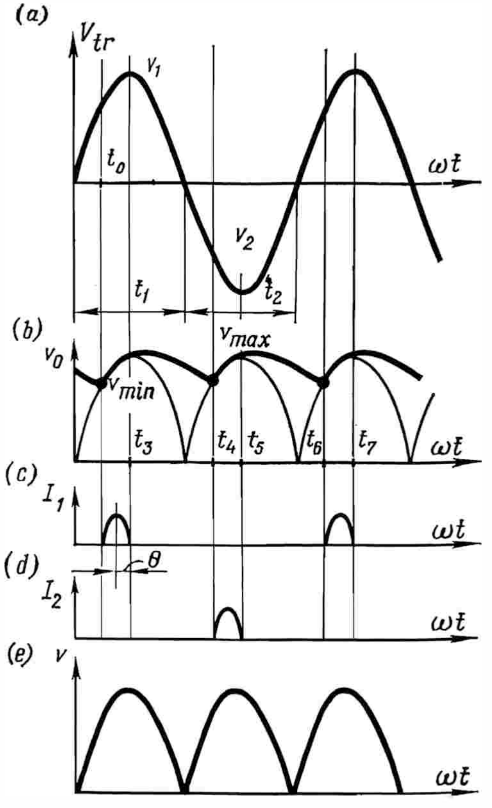


Fig. 51. Current and voltage waveforms of a full-wave bridge circuit
(*a*) transformer winding voltage; (*b*) rectifier output voltage; (*c*) and (*d*) diode current; (*e*) voltage across load in the absence of capacitor C_0

At the initial moment of time t_0, the voltage across capacitor C_0 is v_{min}. Following that moment, voltage v_1 becomes greater than v_0, as a result diodes D_1 and D_4 conduct, and capacitor C_0 charges. At t_3, voltage v_1 attains peak value v_{max}, diodes D_1 and D_4 are cut off and capacitor C_0 discharges. At t_4, the voltage across the capacitor C_0 becomes v_{min}. In consequence, the capacitor recharges through diodes D_2 and D_4 until the voltage of the second phase reaches peak value v_{max} (at t_5). Thus, it is evident

that the current passes through diodes D_1 and D_4 only during a certain part of the full duration of both half cycles of the sinusoidal voltage. This part of the cycles, referred to as the *operation angle* of the rectifier, is denoted by the Greek letter 2θ. Figure 51*e* shows the waveform of the voltage in the absence of capacitor C_0. Comparing the waveforms of Figs 51*b* and *e*, it may be seen that the capacitor ensures considerable attenuation of the d.c. voltage ripple, this being accompanied by an increase in the average value of the voltage.

5.3. Filters

The pulsating voltage appearing at the d.c. side of a rectifier circuit may be treated as the sum of two components, one variable and the other constant. The ratio of the amplitude of the variable component (ripple amplitude) to the constant component of the direct output voltage is known as the *ripple factor* of the rectifier circuit. This factor may be expressed as follows:

$$K_r = \frac{V_{v.c}}{V_{c.c}} 100\%$$

where $V_{v.c}$=amplitude of the variable component

$V_{c.c}$=constant component of the rectified voltage

The variable component of the rectified voltage appears at the output of matching circuits and tends to impair the operation of the measuring and logical elements of the electrical equipment.

The ripple factor is generally reduced by providing a *ripple eliminating (smoothing) filter* between the rectifier and the equipment meant for d.c. supply. Such a filter is made up of reactive circuit elements of different a.c. and d.c. resistance. Low-frequency chokes, high-value capacitors and, also, correspondingly interconnected electronic valves and transistors usually serve as such elements.

Figure 52*a* illustrates the principle of operation of an *inverted*-L *filter* circuit consisting of resistor R and capacitor C.

With respect to the variable component, the inverted-L filter acts essentially as a voltage divider built up of se-

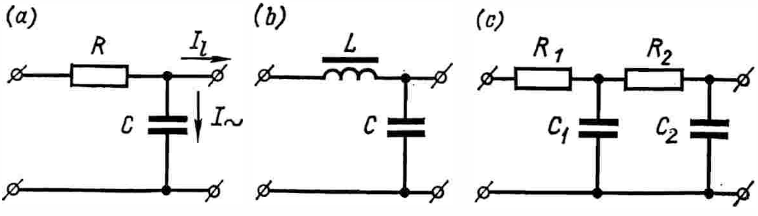


Fig. 52. Low-frequency filter circuits
(a) and (b) inverted-L RC and LC filters; (c) series connection of two inverted-L filters

ries-connected resistor R and capacitive reactance X_C, the latter being equal to

$$X_C = \frac{1}{2\pi fC}$$

where f = the ripple frequency of the rectified voltage
C = the capacitance value of the capacitor (Fig. 52a)

As may be seen from the above equation, the capacitive reactance and, consequently, the variable component of the output voltage diminish with increasing capacitance C.

The variable component of the current flowing through the voltage divider is given by:

$$I_{v.c} = \frac{V_{v.c}}{\sqrt{R^2 + X_C^2}} \tag{6}$$

According to this equation, the variable component current appearing at the output of the filter circuit decreases with increasing resistance of R. Thus, it is evident that the ripple is smoothened out if the filter contains a circuit element limiting the variable component current (i.e., a resistor) and an element offering a low resistance to the current set up by the variable component of the filter output voltage.

The operation of a ripple eliminating filter is characterized by its *ripple smoothing factor* K_s that shows by how many times the ripple factor at the input of the filter is greater than that at the output:

$$K_s = \frac{K_{r.in}}{K_{r.out}}$$

where $K_{r.in}$ =ripple factor at the filter input
$K_{r.out}$=ripple factor at the filter output

The inverted-L filter circuit described above is the most simple and inexpensive of all. It should be noted, however, that the ripple smoothing factor can be raised in this case only by increasing the value of resistance R, this being accompanied by an increase in the d.c. voltage drop across resistor R and a corresponding drop in the efficiency of the filter. The ripple smoothing factor may be improved by connecting two inverted-L filters in series as shown in Fig. 52*c*.

RC filters are used in simple devices for handling small rectified currents (up to 20 milliamperes).

Chokes are often substituted for resistors. This is possible due to the fact that the choke winding is of low resistance (a few ohms) to the constant component current and of relatively high resistance (tens and hundreds of ohms) to the variable component current. Such filters have an efficiency of about 80 to 90 per cent. The circuit diagram of a smoothing filter with a choke is shown in Fig. 52*b*.

5.4. Voltage Stabilizers

In many types of measuring equipment the supply voltage or current is required to be highly stable under conditions of varying mains voltage and varying load; this requirement is met by using voltage stabilizers with the stabilizing (reference) element in the form of gas-filled *voltage stabilizing tubes* or *silicon voltage stabilizers (Zener diodes)*. In modern equipment semiconductor devices are the most widely used.

A stabilization circuit with a voltage reference diode is illustrated in Fig. 53. This circuit consists of a transformer *Tr*, a bridge-type full-wave rectifier, a double-section inverted-L ripple filter, and a silicon stabilitron (reference diode) D_5.

This circuit operates in the following way. The voltage drop across the reference diode corresponds to the section

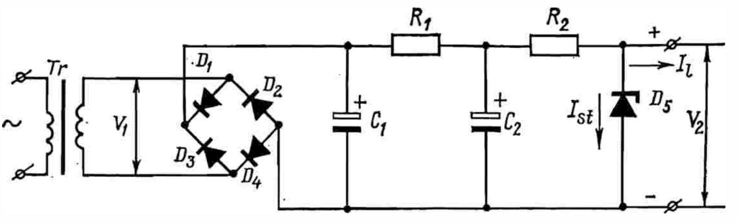


Fig. 53. Parametric voltage stabilizer circuit

of the volt-ampere characteristic featuring a low differential resistance:

$$R_d = \Delta V_{ref}/\Delta I_{ref} \tag{7}$$

where ΔV_{ref} is the increment of the voltage drop across the reference diode due to a change of ΔI_{ref} in the diode current. When this differential resistance is low, even small variations of the voltage drop across the diode result in considerable changes in the diode current; this peculiarity of the reference diode characteristic is utilized in voltage stabilization circuits.

With rise of the mains voltage the voltage across the reference diode (i.e., the output voltage) will also increase, but rather slightly, this being due to a comparatively considerable increase in the reference diode current with corresponding increase of the voltage drop across resistors R_1 and R_2. A drop in the mains voltage will produce an opposite sequence of events.

Any increase in the load resistance will lead to a corresponding increase in the reference diode current and vice versa. The output voltage of the voltage stabilizer will thus be almost constant.

In consequence, the output voltage undergoes but slight changes though the mains voltage and the load resistance vary within considerable ranges. Stabilizers shown in Fig. 53 are known as *parametric*.

Parametric voltage stabilizers feature a comparatively poor efficiency due to considerable power consumption in resistors R_1 and R_2. These stabilizers are used when the load current does not exceed 100 mA. They find application mostly in the simpler types of equipment and are ca-

pable of stabilizing the output voltage to about ± 0.1 per cent.

When heavy load currents or higher degrees of stabilization are required, this is attained by making use of stabilizer circuits containing transistors.

5.5. Amplifiers

The performance of the moving system of measuring instruments often requires a considerable level of drive power to be delivered to a low output resistance. As a rule, the output signals that are proportional to the quantity being measured are of a lower level and are supplied by circuits with high output resistances. To provide the required power gain and match the moving system to the output resistance of the circuits being measured amplifiers are used.

A.c. amplifiers use valves or transistors as the amplifying elements. A single-stage transistor circuit shown in Fig. 54*a* will serve to illustrate the operation of a.c. amplifiers. This amplifier stage consists of transistor T, input and output capacitors C_1 and C_2, resistors R_1, R_2 and R_3 (included into the circuit to stabilize the operating conditions of the transistor against changes produced by variations in the ambient temperature), collector load resistance R_c, and capacitor C_3 whose function is to bypass the a.c. component of the emitter current. The input signal is applied to the transistor base via capacitor C_1. (The input voltage is the voltage measured across terminal V_{in} and earth while the output voltage is taken off terminal V_{out} and earth.)

The base current I_b as a function of the base-emitter voltage $V_{b.e}$ is shown in Fig. 54*b* along with the collector current I_c as a function of the collector voltage V_c. These functions can be used to determine the magnitude of the output signal for a known value of the input signal. To this end a load line should be plotted and a quiescent (operating) point selected on this line, this quiescent point determining the current passed by the transistor and the voltage across it in the absence of an input signal. This load line (AB in Fig. 54*b*) is plotted by connecting point B corres-

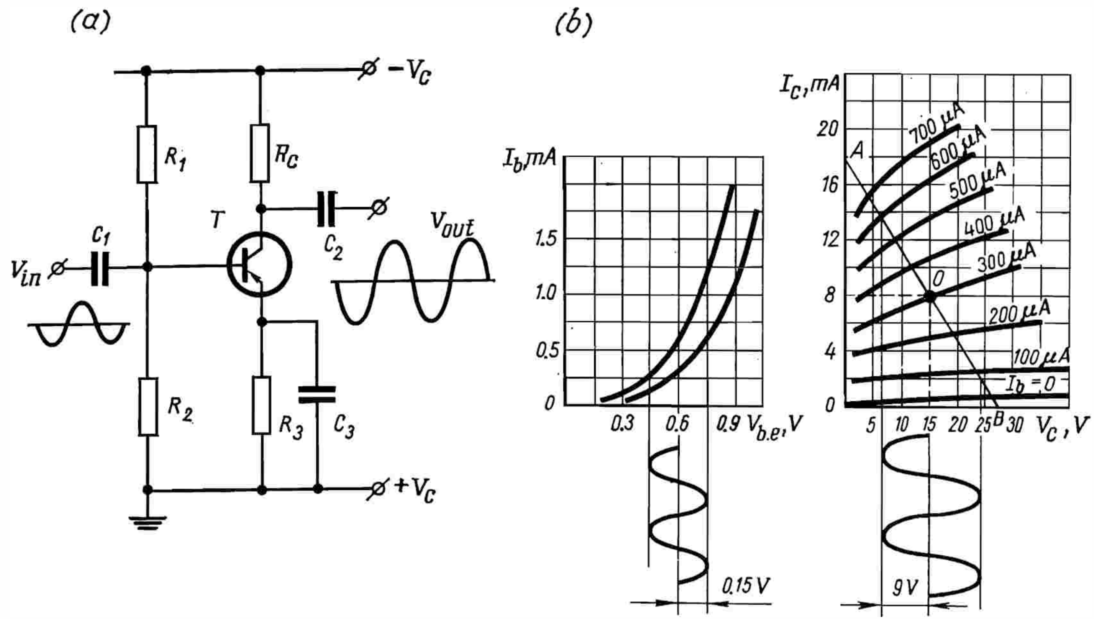


Fig. 54. A.c. amplifier circuit
(*a*) single-stage amplifier; (*b*) transistor input and output characteristic curves

ponding to the supply voltage magnitude on the voltage axis with point A determining the maximum current value ($I_{c.\max}=V_c/R_c$) on the current axis.

Let us assume that the selected quiescent point corresponds to the intersection of the load line with the transistor output characteristic at a base current of 300 microamperes; in other words, to provide transistor operation at this quiescent point the transistor base should be fed with a 0.3-milliampere current. This corresponds to a point $I_b=0.3$ milliampere and $V_{b.e}=0.6$ volt on the transistor input characteristic. Suppose the input signal to be a sine wave with an amplitude of 0.15 volt. During one half cycle of this input signal the base current will increase from 0.3 to 0.6 milliampere and the collector current will correspondingly increase from 8 to 13.5 milliamperes. This will result in a drop in collector voltage from 15 to 6 volts. Thus, a 0.15-volt change in input signal magnitude results in a 9-volt variation of the output voltage; in other words, this means that the stage provides signal amplification.

Modern multistage a.c. amplifiers are designed to handle very low input signals (of the order of fractions of a microvolt) and have very high gains (from 10^6 to 10^{12}).

D.c. amplifiers are subdivided into direct-coupled amplifiers and amplifiers with frequency conversion. Direct-coupled amplifiers feature a considerable instability of the output signal with zero input signal (the so-called *zero drift*) and, consequently, can be employed only in measuring equipment that can be calibrated as many times as required and that is designed to operate within a rather narrow temperature range.

Amplifiers with frequency conversion feature very low zero drifts and can be used for very long periods of time (up to several years) without additional calibration. As a rule, automatic measuring equipment utilizes this type of amplifier.

The input d.c. signal is converted into an a.c. signal with the aid of a mechanical or electronic signal transducer. The block-diagram of a d.c. amplifier with frequency conversion is presented in Fig. 55. In the input signal transducer ST_1 the input d.c. signal is converted into an a.c. one and then amplified by the a.c. amplifier *AMP*. The

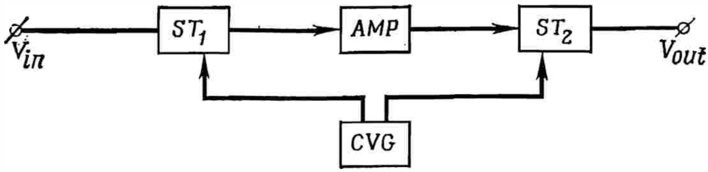


Fig. 55. Block-diagram of a d.c. amplifier with signal conversion

amplified a.c. signal is fed from this amplifier to the output signal transducer ST_2, where it is converted into a d.c. signal. Both transducers are controlled by a conversion voltage generator (CVG).

5.6. Multivibrators

Square voltage waveforms and rapidly changing voltages are produced with the aid of relaxation oscillators (multivibrators, coupling oscillators).

Multivibrator circuits generate almost square voltage waveforms. In essence, a multivibrator circuit is composed of a two-stage resistance-coupled amplifier with the output connected back to the input. Multivibrators can be used under three kinds of operating conditions: free-running (dynamic), synchronized, and flip-flop.

Under free-running conditions the multivibrator operates as an oscillator and the output signal generated is practically independent of external influence. Under synchronized conditions the repetition rate of the output pulses is determined by an external synchronizing signal. When employed as a flip-flop the multivibrator generates an output pulse in response to an actuating input signal. Multivibrator circuits can be designed with electron valves or transistors (Fig. 56).

In the symmetrical multivibrator shown in Fig. 56a, $R_{b1}=R_{b2}$, $R_{c1}=R_{c2}$, and $C_{b1}=C_{b2}$. When the supply voltage V_c is turned on, transistors T_1 and T_2 will begin to conduct collector currents I_{c1} and I_{c2}. Capacitors C_{b1} and C_{b2} will charge to a voltage

$$V_{c1}=V_{c2}=V_c-I_cR_c \tag{8}$$

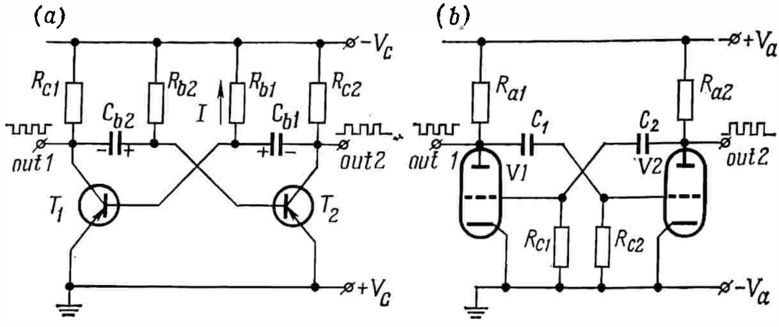


Fig. 56. Multivibrator circuits
(*a*) transistor version; (*b*) valve version

The collector currents, however, cannot remain stictly equal for a long time. Due to fluctuations (fluctuations are random deviations of electron densities from a uniform distribution resulting from the thermal motion of electrons in gases, fluids, or solids) the collector current of one of the transistors (say, that of T_2) will rapidly exceed that of the other. According to equation (8) this will result in a higher voltage drop across R_{c2} and, consequently, in a lower collector voltage V_{c2}. In such a case capacitor C_{b1} will begin to discharge, the discharge circuit being as follows:

$$C_{b1} \rightarrow R_{b1} \rightarrow V_c \rightarrow T_2 \rightarrow C_{b1}$$

Consequently, the base of transistor T_1 acquires a positive potential with respect to the transistor emitter that brings about a further decrease in the collector current of this transistor. A drop in the collector current I_{c1} will produce a lower voltage drop across R_{c1} and a higher voltage on the collector of T_1. This in turn will cause additional charging of capacitor C_{b2} along the following path:

$$C_{b2} \rightarrow R_{c1} \rightarrow V_c \rightarrow T_2 \rightarrow C_{b2}$$

This charging current will produce a positive voltage drop across the emitter-base junction of transistor T_2, tending to further increase the collector current I_{c2}. Such a sequence of events will proceed until the current through

transistor T_1 drops to zero and the current through T_2 attains maximum magnitude.

This process of cutting off transistor T_1 and opening up transistor T_2 to its utmost goes on in an avalanche-like manner, i.e., the circuit is switched to this state abruptly. Transistor T_1 will be cut off as long as the negative potential on its base exceeds the magnitude of the cutoff voltage; this potential is produced by the discharge current of C_{b1} flowing along the following path:

$$C_{b1} \to R_{b1} \to V_c \to T_2 \to C_{b1}$$

In this state of the circuit the voltage at output *1* is almost the same as the supply voltage V_c, while at output *2* the voltage is nearly zero (actually, the voltage drop across transistor T_2).

During the discharge of capacitor C_{b1} the discharge current gradually drops, causing a corresponding decrease in the absolute value of the voltage drop across resistor R_{b1}. When finally this voltage drop attains the magnitude of the opening voltage of transistor T_1, this transistor begins to conduct current. By this moment of time capacitor C_{b2} has already charged to the full supply voltage. The collector current of T_1 will produce a certain voltage drop across R_{c1} and this will initiate the discharge of capacitor C_{b2} through transistor T_1 and resistor R_{b2}. This discharge current will produce a voltage drop across resistor R_{b2} that tends to turn this transistor off, since the voltage is positive in respect to the transistor base.

This sequence of events continues until transistor T_1 is turned on to its utmost, transistor T_2 is completely cut off. The voltage at output *1* in this state of the circuit will drop to almost zero and the voltage at output *2* will attain a value of nearly the supply voltage. The described cycles of capacitor charge and discharge will be repeated, generating output waveforms of a nearly rectangular pattern, as shown in Fig. 56. The time required to switch the circuit from one state to the other is very short, i.e., of the order of fractions of a microsecond. Multivibrator circuits employing electron valves operate in a similar manner.

The amplitude of the output pulses (the pulses at the

transistor collectors) is almost equal to the supply voltage, while their duration can be determined from the following equation:

$$t_1 = t_2 = 0.7\,R_b C_b \tag{9}$$

where t_1 and t_2 are the pulse durations.

As can be seen from equation (9), the repetition rate of multivibrator output pulses can be controlled by varying the magnitudes of resistors R_b and/or capacitors C_b.

5.7. Trigger Circuits

Electronic circuits having two stable states are called *trigger circuits*. A distinctive feature of trigger circuits is that they can be switched from one state to the other by an external signal and returned to the initial state with the next actuating pulse. Transition from one state to the other takes place abruptly and, consequently, the output waveforms closely resemble a rectangular pulse.

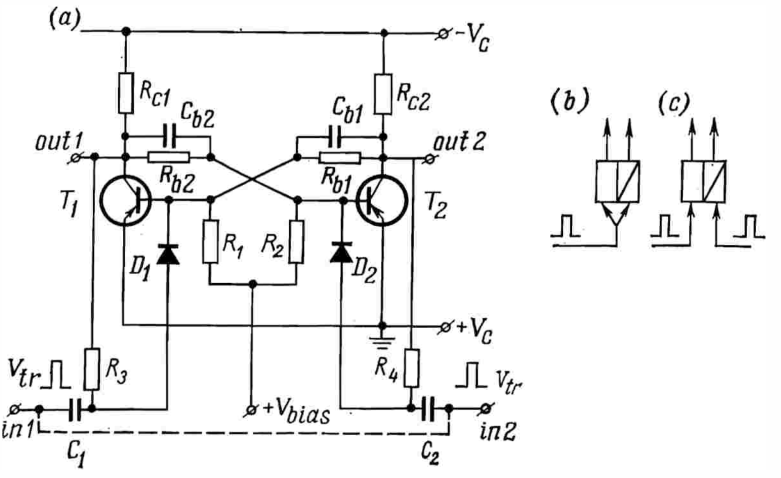


Fig. 57. Transistorized trigger circuit

(a) circuit diagram; (b) and (c) functional representation of circuits with one and two inputs, respectively

A transistorized version of a symmetrical trigger circuit is presented in Fig. 57*a*. This circuit can operate with one input as well as with two. In the latter case the trigger circuit is switched by applying positive triggering pulses to the transistor bases via input capacitors C_1 and C_2; in the former case both inputs are to be connected as shown in the drawing by a broken line and the actuating pulses applied to this common point.

In a symmetrical trigger circuit

$$R_{c1}=R_{c2};\ R_{b1}=R_{b2};\ C_{b1}=C_{b2};\ R_1=R_2;\ R_3=R_4;\ C_1=C_2$$

When the circuit is first switched on an unstable symmetrical mode of operation may be set up. However, due to the random fluctuations in the transistor currents, the collector voltage on one transistor will drop below that of the other. Assume, for instance, that the collector voltage of T_2 has decreased; this will result in a lower base potential of T_1 (relative to the emitter) and thus in a lower collector current. In turn this will produce a higher collector voltage on T_1, an even higher potential on the base and lower collector voltage of T_2, etc. This process takes place in an avalanche-like manner and ends with transistor T_1 being securely cut off and transistor T_2 opened to its utmost. In other words, the trigger circuit will be switched to one of its stable states. This state will be maintained for an indefinite period of time, since the base of the transistor that is cut off is at a voltage determined by the ratio of the arms of voltage divider R_1-R_{b1} and does not vary with time. To switch the trigger circuit to its other steady state a triggering pulse cutting off transistor T_2 (or turning on transistor T_1) is to be applied to the circuit input. A positive pulse on the base of transistor T_2 will cut it off and the potential on its collector will begin to drop. This will cause a current to appear in the base of transistor T_1, this transistor will begin to conduct current with a corresponding increase in the collector voltage. This change in collector potential is applied to the base of transistor T_2, tending to cut it off. The process will go on until transistor T_1 is turned on to the utmost with transistor T_2 being completely cut off. An external

positive bias voltage V_{bias} assures that the transistors are reliably cut off.

Standard designations of trigger circuits are given in Figs 57*b* and *c*; here the trigger branches are shown as rectangles with the branch containing the conducting transistor depicted as a rectangle with a diagonal, this meaning that the output signal at this branch is a binary zero. The input actuating pulses and the output signals are shown by arrows.

Trigger circuits are widely used in binary counters, various commutating (switching) devices, as memory elements, etc.

The principle of trigger circuit operation with switching elements in the form of electronic valves is in essence the same as for transistorized circuits and for that reason is not discussed.

5.8. Comparators

Comparator circuits constitute one of the main elements of any automatic measuring equipment. Their function is to compare the voltage V_x being measured with a reference voltage V_{ref}. The reference voltage is provided by some kind of standard source. In some cases this reference voltage is to be of a certain waveform and is generated by a special oscillator, then fed to a sensing device to be compared with the voltage being measured. Comparator circuits are characterized by the following main parameters: sensitivity, responsiveness, input resistance, stability of operation (long-term stability, as well as the ability to operate normally under changing ambient conditions, varying mains voltage, etc.), reliability, sensitivity to external interference. The block-diagram of a comparator circuit is presented in Fig. 58. The sensing device of the comparator responds to the torque produced by comparing the measured and reference signals. The output of the sensing device is amplified and applied to a controlling device designed to control certain circuit elements. To raise the sensitivity and improve the linearity some comparator circuits are provided with feedback.

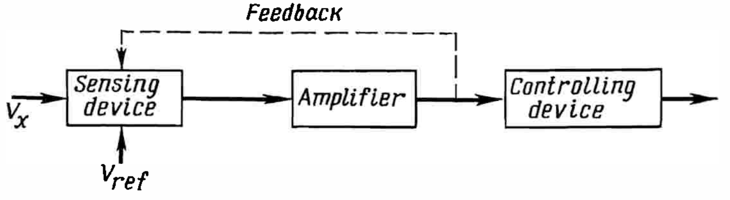


Fig. 58. Comparator block-diagram

As an example of the simplest type of comparator the moving-coil meter can be cited. In such meters the torque produced in the coil by a current flowing through it is compared with the restoring torque of the instrument spring. Electromagnetic relays are another example.

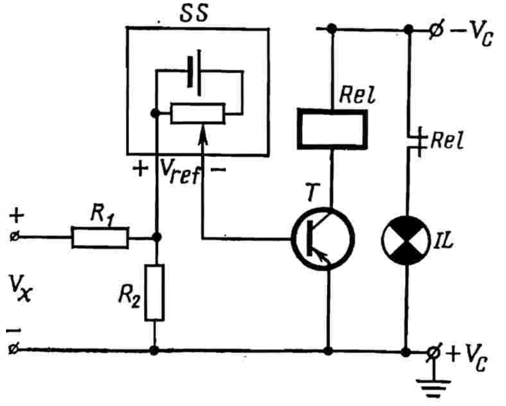


Fig. 59. Comparator circuit

A comparator circuit designed to control a voltage is shown in Fig. 59. When the voltage under measurement V_x is considerably lower than the reference voltage V_{ref} provided by a standard voltage source *SS*, transistor *T* conducts current due to the negative voltage applied across its base. In this case the relay armature is pulled in,

since the transistor current passes through the relay winding. The normally closed relay contacts are opened, thus breaking the circuit of indicating lamp *IL*. At a certain value of the voltage V_x the negative base voltage drops to a magnitude corresponding to a collector current that is lower than the relay holding current. The relay armature will be released, the contacts will be closed, and the indicating lamp will light up.

A circuit of this kind can be used to sort diodes by their resistance in the conducting direction. When the forward voltage drop, in this case V_x, exceeds certain predete mined values. the indicating lamp will light up, showing that the diode is to be rejected. The circuit can be adjusted to any desired value of admissible forward voltage drop simply by means of a potentiometer of the standard voltage source.

5.9. Fundamentals of Logical Elements

In automatic measuring equipment electromechanical relays are usually replaced by electronic switching circuits, this improving the equipment reliability due to the absence of moving parts, the independence of the equipment life from the number of switching operations performed, lower sensitivity to changes in surrounding conditions. Electronic switching circuits employed in automatic equipment are often termed logical elements as each of them is capable of performing a certain logical operation, such as "OR", "AND", "NO", "MEMORY", "DELAY", etc.

When a circuit performance is similar to that of a relay, the circuit can be described as featuring two states. Conventionally, these states are designated by a zero (0) and unity (1), the latter being used to describe signals of a level differing from zero (for instance, plus 10 or minus 10 volts) while the former is used to describe signals of a zero level.

In logical elements using electromechanical relays the "1" signal corresponds to a closed circuit of the relay x winding and the "0" signal to an open circuit, as illustrated in Fig. 60.

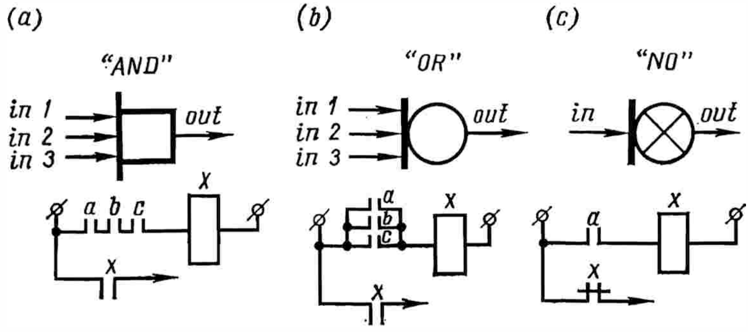


Fig. 60. Functional representation of main logical elements
(*a*) "AND" circuit; (*b*) "OR" circuit; (*c*) "NO" circuit

The circuits of several elements used to perform certain logical operations are shown in Figs 60 and 61. The relay versions for the "AND", "OR", and "NO" operations are illustrated in Fig. 60. Standard circuit designations are used to simplify the process of drawing circuits containing logical elements.

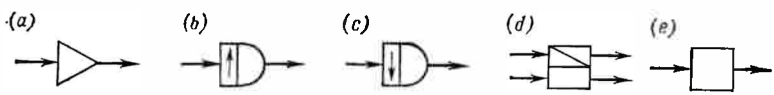


Fig. 61. Functional representation of auxiliary logical elements
(*a*) "AMPLIFICATION"; (*b*) "DELAY" in response to input signal; (*c*) "DELAY" in response to disappearance of signal; (*d*) "MEMORY" (trigger circuit); (*e*) "REPETITION"

Circuits composing a logical network can, as a rule, be designed and analysed using the main three logical circuits, namely, the "AND", "OR", and "NO" circuits performing the operations of logical multiplication, addition, and negation, respectively.

Logical multiplication ("AND") can be performed with the aid of a circuit shown in Fig. 60*a*. This circuit features a certain n number of inputs (three in the circuit under consideration) and a single output. In algebraic form the multiplication operation may be written as follows:

$$a \times b \times c = x$$

where x =output signal
a, b, c =input signals

Assuming the input signals to be either "1" or "0", we obtain, for instance: $1\times1\times1=1$; $1\times1\times0=0$ and so on. In other words, in an "AND" circuit the "1" input signal can be obtained only when all the input signals are "1", i.e., when all the inputs are actuated.

Logical addition ("OR") can be accomplished with the aid of the circuit shown in Fig. 60*b*. This circuit also has n inputs and a single output. In algebraic form the operation of addition may be written as:

$$a + b + c = x$$

The input signals (a, b, c) can be either unity or zero and, consequently, the output signal can be $1+1+1=1$; $1+0+0=1$; $0+0+0=0$, etc. In other words, the output signal is zero only in the absence of all input signals.

Logical negation ("NO") can be accomplished with the aid of the circuit shown in Fig. 60*c*. This circuit has one input and one output. A unity input signal produces a zero output, and vice versa, a zero input signal corresponds to a unity output signal. In algebraic form the "NO" operation may be expressed as:

$$\bar{a} = x$$

In the adopted binary system this will correspondingly be:

$$\bar{1} = 0, \ \bar{0} = 1$$

Figure 61 illustrates the standard circuit designation of logical elements performing the following operations:

"AMPLIFICATION";

"DELAY" in the response to an input signal;

"DELAY" in the response to the disappearance of an output signal;

"MEMORY" (trigger circuit);

"REPETITION".

Logical "AMPLIFICATION" provides an output signal of a higher level than that of the input signals,

The "DELAY" operation provides the appearance (or disappearance) of an output signal after a time interval t has elapsed beginning from the moment of the application of the input signal. The magnitude of this time delay can be set during circuit adjustment, as it is determined by the circuit elements.

Various types of logical elements are available, the main among them being the potential, pulse-potential, and magnetic types (the latter type utilizes the properties of magnetic cores with a square hysteresis loop).

Equipment employing electronic relays features high switching rates and long life, as well as high reliability of operation. Manufacturers guarantee a failure in no less than 40 thousand hours of continuous operation of these electronic circuits, regardless of the number of switching operations performed (for comparison, electromechanical relays feature a reliability of about one failure for no less than 1 million switching operations).

At present several types of miniature logical elements (micromodules) of very small size are available;

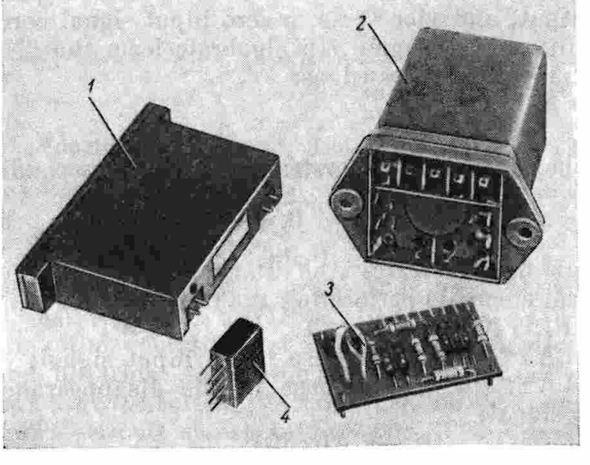


Fig. 62. Electronic logical elements
1, 3, and *4*—semiconductor elements; *2*—magnetic logical element

with the advent of these elements the size of the equipment can be reduced by a factor of 100 to 200 and its power consumption becomes 10 to 50 times less. Micromodules feature a higher reliability and are even less sensitive to external interfering signals than usual logical elements.

Figure 62 shows some typical logical elements.

5.10. Measuring Equipment and Wiring

All measuring instruments should meet the following basic requirements: accuracy and stability of measurements; simplicity of adjustment and maintenance procedures; high interference resistance; reliability; capability to function normally under conditions existing in workshops with mass-scale production of semiconductor devices. The circuit and equipment design are to a great degree responsible for the realization of these requirements. The equipment can be designed in single-unit, multi-unit, and block-module versions.

Single-unit designs are often used in equipment intended to measure one or several parameters of a semiconductor device, in cases when the electric circuit is comparatively simple and of not too great a volume. In the single-unit design all the circuit elements are mounted on one common chassis.

Block-module designs are used when the circuit is a complex one, consisting of a considerable number of functional elements (such as logical elements, amplifiers, multivibrators, etc.). In this case the various elements are designed as separate modules and are then mounted on a common panel, that is connected to the rest of the circuit either by soldered joints, or with the aid of connectors.

Electronic equipment of block-module design provides for easy manufacture. A plug-connected panel of block-module design is shown in Fig. 63.

Multi-unit constructions are used when the equipment is a very complex one. In this case the equipment is designed in the form of separate units interconnected by means of a flexible wire bunch. In this design a failure can be quickly traced and the faulty unit replaced. Depending

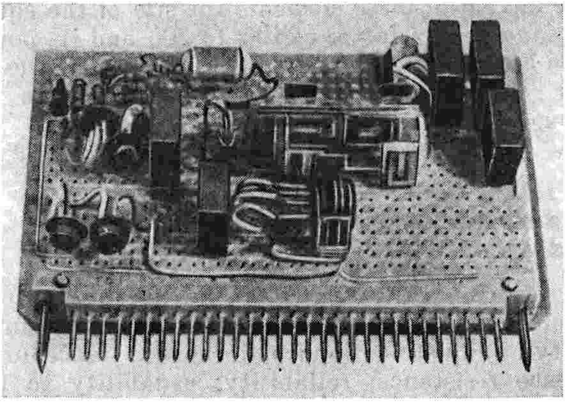


Fig. 63. Block module

on the requirements, the units in measuring equipment can be manufactured using conventional wiring methods with individual circuit elements wired to the common board, or with the aid of printed wiring; the most modern types sometimes utilize microminiaturization techniques (thin-film and integrated circuits).

In case of small-scale production, when only one or several specimens of the equipment are to be manufactured, conventional wiring methods are usually employed. Printed wiring is used when the scale of equipment production is large enough to pay off the cost of printed wiring designing. Thin-film and integrated circuits are employed when the equipment should meet extremely severe requirements as regards its reliability, volume, and weight.

The wiring is done in strict accordance with the wiring diagram and technical specifications.

Wiring with the aid of flexible bunched wires is performed in the following order:

wiring separate wiring cards or boards, switches, and other separate units or subunits (before mounting them onto the common chassis);

making jumper connections;

laying separate flexible wires and joining them into a bunch;

mounting separate units and subunits onto the common chassis;

laying the bunch on the chassis and soldering its wires to the corresponding points of units and subunits;

wiring of leads-mounted individual circuit elements, such as resistors, capacitors, etc.

Connections to be soldered must have pretinned leads. Wires and leads of elements are passed through holes in the wiring tags, twisted around them, then crimped, and finally soldered. As a rule, not more than two wires or element leads are to be soldered to one tag.

Soldering is done with the use of a soldering iron, a tin-lead solder, and a colophony flux. Splicing wires by overlapping or joining them end-to-end with subsequent soldering is inadmissible, as well as the use of soldering acids.

In cases when greater mechanical strength of the joint is required, arc welding is substituted for soldering.

With printed wiring units the equipment wiring is performed in the following order:

the circuit elements are prepared for wiring, i.e., their leads are tinned, bended, and trimmed to the desired length;

the leads-mounted elements are installed;

the elements are soldered into the printed wiring. This is usually accomplished either by dipping into the melted solder or by means of a solder wave.

Checking the wiring consists in assuring its accordance to the wiring diagram and inspection for faulty joints. The mechanical strength of the wiring is tested on a vibration and shock test stands.

5.11. Adjustment of Measuring Equipment

The units and subunits used in measuring equipment are to be adjusted (tuned) after manufacture. After this tuning operation the units and subunits must conform to specifications. The adjustment is performed with the aid of tunable elements provided in the circuit, such as taps on transformer windings, variable resistors and capacitors, tunable cores in tuned circuits, etc. In certain strictly limited cases element selection can be used,

The first subunit to be adjusted is the power supply; here the output voltage is checked and made to comply with specifications.

After this, using the voltage calibration chart that goes with the circuit diagram, the voltage at various selected points of the circuit is checked; the selected points are usually the leads of valves or transistors. The operating conditions of these elements are usually checked by means of a universal tester or a valve voltmeter.

Generators of special voltage waveforms are used to adjust and test the performance of amplifiers, pulse-forming networks, triggers, counters, limiters and so on, i.e., in those cases when the device requires a certain specified input signal for normal operation. The output signal of such a generator can be set to the required level and waveform and controlled by means of an oscilloscope or a valve voltmeter. In certain cases double-beam oscilloscopes are of great advantage as they give a simultaneous display of the input and output signals of a unit or circuit undergoing tuning, or the equipment as a whole. Test generators of sine and special waveforms are in turn controlled with the aid of oscilloscopes and special valve voltmeters.

To imitate the actual conditions in which the unit or circuit is to operate in the equipment, all adjustment operations must be performed with dummy loads at the output and input terminals. These dummy loads can be in the form of resistors, capacitors, inductance coils, etc., as the case might be.

Adjustment of the functional part of the measuring equipment, in which logical elements predominate, is usually carried out with the aid of various kinds of special accessories that imitate the functions of comparators, limit switches, metering devices, etc.

REVIEW QUESTIONS

5.1. Describe the function of a rectifier.
5.2. Sketch the main rectifier circuits.
5.3. For what purpose are filters used?
5.4. Write down the expressions for the ripple factor and the ripple smoothing factor of a rectified voltage.
5.5. Sketch the main ripple filter circuits.

5.6. Describe the performance of a parametric voltage stabilizer.
5.7. Sketch the circuit of a single stage of a.c. amplification.
5.8. Why is signal conversion needed in d.c. amplifiers?
5.9. Describe the performance of a multivibrator circuit.
5.10. Give the expression describing the pulse duration for multivibrator circuits.
5.11. Sketch a trigger circuit with one and two inputs.
5.12. In what cases are comparators employed?
5.13. Define a logical element.
5.14. Sketch the functional circuits of main logical elements.
5.15. Enumerate the main design versions used in measuring equipment.
5.16. In what order are wiring operations performed?
5.17. How is adjustment made?

CHAPTER SIX

Measurement of Electrical Parameters

6.1. Purpose and Methods of Measurement

Depending on their purpose, measurements of the electrical parameters of semiconductor devices fall into three groups:

(1) intermediate measurements;

(2) classification measurements;

(3) test measurements.

Measurements of the third group are discussed at length in Chapter Eight.

Intermediate measurements are made after certain technological operations in order to check the manufacturing process and maintain a stable percentage of devices meeting specifications.

These measurements are to be carried out after operations that are liable to affect one or another parameter of the device under consideration. For instance, measurements are made after mechanical processing (cutting, etching) of the *p-n* junction, after the junction has been subjected to temperature treatment (soldering the crystal to its support, see Chapter Four).

In cases when these measurements reveal that one or several parameters of a stock product do not meet requirements, the semiconductor device should be rejected. This eliminates any further useless expenditure of labour and material. Moreover, such measurements provide for effective control of the manufacturing process.

Classification measurements are measurements carried out to class the type of the semiconductor device after the manufacturing cycle is completed. In these measurements only the main parameters are measured. The values obtained are compared with those specified for each type of the given series.

As a rule, the semiconductor devices are made to meet more stringent electrical requirements than the requirements specified in the certificate of the device. Depending on the type of the semiconductor device and actual conditions of operation the safety margin may be up to 50 per cent. This is done to improve the reliability of the devices in service.

The type of the semiconductor device is established by comparing the measured parameters with those specified.

In modern manufacturing processes the parameters of semiconductor devices can be measured manually or automatically or, alternatively, by a combination of both methods.

This chapter deals with measurement of the main parameters of modern semiconductor devices. The parameters measured during mass-scale production are listed in Table 2. The procedure of measuring certain parameters of semiconductor devices is but briefly examined since these measurements are rather sophisticated.

Furthermore, measurements carried out before the cycle of manufacture of the semiconductor device proper (for instance, measurements of the surface resistivity of wafers) are omitted since they fall beyond the scope of this book.

A detailed description of these methods can be found in special publications.

The considerable dependence of the device parameters on temperature imposes certain limitations on the methods used for their measurement.

The parameters are to be measured immediately after the voltage or current has been applied (or after a specified time interval has elapsed, usually, several seconds) so as to avoid an excessive temperature rise. Moreover, the reverse current and then the other parameters should be measured.

When measurements are liable to cause such a temperature rise, special measures should be taken to ensure adequate heat dissipation. Usually this is achieved by following means:

absorption of the developed heat by a massive framework of the equipment being measured;

Table 2

Semiconductor Device Parameters Measured During Manufacture

Diodes	Rectifier	V_{for}; $V_{rev.\,max}$; I_{rev}; I_{rec}
Diodes	High-frequency and microwave	V_{for}; $V_{rev.\,max}$; I_{rev}; $I_{for.\,max}$; Δf; C; Q
Diodes	Pulse	V_{for}; $V_{rev.\,max}$; I_{rev}; $I_{for.\,max}$; $R_{p.\,max}$; τ_{off}
Diodes	Reference	V_{for}; $V_{rev.\,max}$; I_{rev}; $I_{for.\,max}$; V_{st}; R_d
Diodes	Switching: uncontrolled	$V_{for.\,max}$; $V_{rev.\,max}$; I_{rev}; $I_{for.\,max}$; V_{sw}; I_{sw}; I_{cutoff}; V_{res}; I_{leak}
Diodes	Switching: controlled	$V_{for.\,max}$; $V_{rev.\,max}$; I_{rev}; $I_{for.\,max}$; V_{sw}; I_{sw}; I_{cutoff}; V_{res}; I_{leak}; I_{con}; V_{con}
Diodes	Varicaps (varactors)	C_{rated}; V_{bias}; Q
Diodes	Tunnel (Esaki)	I_{max}; C; V_{max}
Diodes	Laser	P_{rad}; λ; $P_{rad} = f(\lambda)$
Photodiodes		I_d; I_s
Transistors		$I_{c.\,rev}$; $I_{e.\,rev}$; h_{22}; f_α; $\lvert\beta\rvert$; f_{max}; K_n; g_{stat}; $V_{c.\,sat}$; $V_{b.\,sat}$; $r_b' C_c$; C_c
Phototransistors		I_d; I_s

dissipation of heat into the surrounding atmosphere by special radiators;

cooling with special liquid or gaseous heat-transfer agents (oils, liquid nitrogen, etc.).

The measuring instruments should be of appropriate accuracy. The accuracy class of the instrument to be used for the given device is stipulated in its specifications and is usually of an accuracy class not lower than 1.5.

6.2. Rectifier Diode Measurements

Rectifier diodes are classified according to the following parameters:

maximum reverse voltage at a predetermined reverse current $I_{rev.max}$;

value of rectified current I_{rec}.

A parameter of great importance is the range of operating frequencies of the diode (sometimes the maximum operating frequency f_{max} is specified). In cases when the frequency of a.c. voltage applied exceeds maximum value f_{max}, the diode losses become very high and cause an impermissible temperature rise.

According to the results of classification measurement the diodes are divided into types within the series under consideration.

Intermediate measurements, as well as classification measurements, are to be made in modern production. In both cases, the same parameters can be measured: in the first case the crystal with a *p-n* junction and a stock product are measured, in the second, the completed diode.

Measuring the volt-ampere characteristic of a *p-n* junction with an oscilloscope. The crystal with the *p-n* junction is connected to a circuit containing a source of a.c. supply and its volt-ampere characteristic is displayed on the screen of an oscilloscope. The connection is made with the aid of a special test probe shown in Fig. 64. Test probes of this type are used for making certain measurements before the crystal is mounted onto its support.

Plastic case *1* houses metal pin *2* that can move freely along the longitudinal axis of the test probe, and is fixed rigidly to knob *3*. Flexible lead 4 soldered to the pin is pas-

sed through the hole in the upper part of the knob. The other end of the lead is connected to a measuring circuit. Plastic cap *5* provided with a duct is screwed onto the case. The cap is screwed onto the case so as to form a common air duct. The duct within the plastic cap is terminated by pipe union *6*. Normally pin *2* is kept in the upper position by spring *7*. The air inside the inner cavity of the case is pumped out via duct *8*, longitudinal grooves in the lower part of the pin, and a flexible rubber tube fitted on pipe union *6*. As a result, air is sucked continuously into the test probe.

For making measurements tip *9* is brought into contact with the upper surface of the crystal. Due to the difference in air pressure on the upper and lower surfaces of the crystal the latter is pressed firmly against the tip and in this way transferred to the

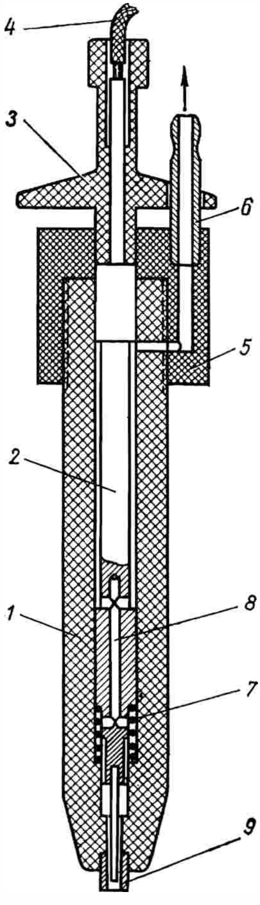


Fig. 64. Test probe for high-voltage *p-n* junction measurements

1—case; *2*—pin; *3*—knob; *4*—lead; *5*—cap; *6*—pipe union; *7*—spring; *8*—duct; *9*—tip.

site of measurement. Then the low surface of the crystal is brought into contact with one of the terminals of the measuring circuit. The measuring circuit is closed by pressing knob *3*, thus bringing pin *2* down and ensuring a reliable electric contact with the upper surface of the crystal.

By examining the volt-ampere characteristic of *p-n* junction curves displayed on the screen of an oscilloscope, crystals with reverse currents above specified value as well as

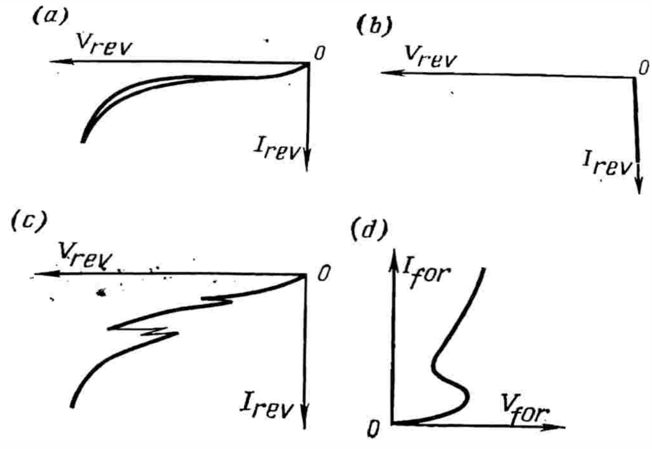


Fig. 65. Examples of distorted volt-ampere characteristics
(*a*), (*b*), (*c*) distortions of reverse branch; (*d*) distortions of forward branch

crystals with distorted characteristic curves can be quickly detected.

Examples of distorted volt-ampere characteristics are given in Fig. 65. Distortions of the type shown in Fig. 65*a* are caused by penetration of moisture into the crystal. The distortion shown in Fig. 65*b* is due to a short-circuited reverse branch. Figure 65*d* shows the volt-ampere characteristic curve of a *p-n* junction that has acquired switching features as a result of improper processing.

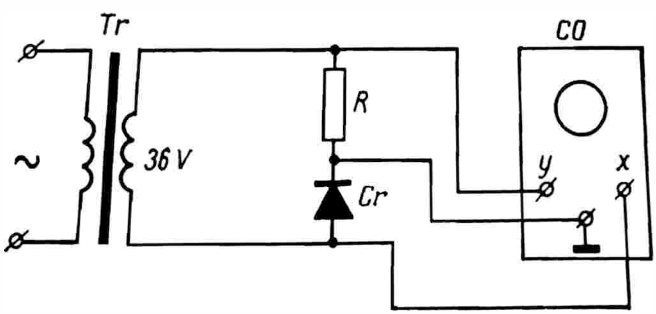


Fig. 66. Circuit for *p-n* junction volt-ampere characteristic display

The circuit for checking the volt-ampere characteristics of *p-n* junctions is shown in Fig. 66. The crystal *Cr* under measurement is connected to the secondary winding of a step-down transformer and acts as a halfwave rectifier. To avoid any breakdown or damage of the surface of the crystal at the point of contact, the measurements are correspondingly made at a low voltage and small current. This condition is also maintained for other measurements of the *p-n* junction.

The current flowing through the *p-n* junction produces a voltage drop across resistor R, this voltage drop being, by Ohm's law, directly proportional to the current in the circuit at any moment of time. This voltage is applied to terminals y of the vertical deflecting plates of the oscilloscope *CO* tube. The supply voltage brought up to the *p-n* junction is applied to terminals x of the horizontal deflecting plates. As a result, the trace left by the electron beam on the screen of the oscilloscope tube represents the dependence of the *p-n* junction current on the voltage drop across the junction.

With proper adjustment of the oscilloscope the reverse branch of the characteristic will be displayed while the forward branch will be blanked out, since a heavy forward current flows at a small voltage drop.

Classification measurements. The diode parameters are measured both with direct (*static conditions of operation*) and alternating (*dynamic conditions of operation*) current. The choice between the static or dynamic conditions of operation is influenced primarily by the following considerations:

1. Under static conditions of operation it is possible to measure the parameters of the reverse branch of the volt-ampere characteristic with the forward branch parameters constant. This is important in cases when high power dissipation on the *p-n* junction is to be avoided (this will be discussed in detail later on).

2. The static conditions of operation are more severe as regards the reverse current, since the latter remains constant throughout the measurement. This makes it possible to detect any flaws in the protection of the *p-n* junction.

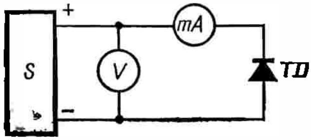
3. Under dynamic conditions of operation it is possible

to measure the average current and, consequently, estimate the rectifying properties of the diode.

4. Under dynamic conditions of operation the diode is subjected to the combined effect of both the forward and reverse voltage. Measurements made under such conditions yield the most satisfactory results.

Static conditions of operation. Both *p-n* junction crystals and finished diodes can be measured by this method.

Fig. 67. Circuit for measuring reverse branch of volt-ampere characteristics



A circuit for measuring the parameters of the reverse branch of a diode volt-ampere characteristic is shown in Fig. 67. The diode *TD* under test (*p-n* junction) is operated from a stabilized source *S* of d.c. supply by reverse voltage. During these measurements the value of the reverse current flowing through the diode is shown by milliammeter *mA* and the reverse voltage is measured with the aid of voltmeter *V*. This method is adopted due to the possibility of stabilizing the d.c. current easily by means of an electronic stabilizer circuit and, therefore, maintaining a highly constant value of reverse current for all diodes under measurement, irrespective of their resistance in the reverse direction.

During intermediate measurements *p-n* junctions with a reverse voltage V_{rev} below specified value are rejected. During classification measurements depending on the value of the reverse voltage measured the diode should be referred to one or another type of construction in accordance with the specifications.

The forward branch of the volt-ampere characteristic is not measured under static conditions of operation since in the case of rectifier diodes it is important to establish the value of the rectified forward current.

Dynamic conditions of operation. The diode under measurement operates as an a.c. halfwave rectifier. During these measurements the value of the forward current is set by the magnitude of the average rectified current, whereas the

reverse voltage, by the peak value of the a.c. voltage of the diode. The parameters measured, V_{for} and I_{rev}, are described by their average values. The average value of the forward current is obtained directly from the readings of a permanent-magnet moving-coil instrument. The instrument measures the current through the diode being measured when a forward voltage half cycle is applied to it. The reverse current flowing through the instrument during the negative half cycles will not cause any appreciable changes in the ammeter readings since the reverse current is thousands of times smaller than the forward current.

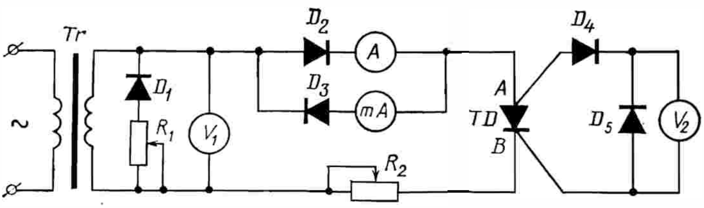


Fig. 68. Circuit for measuring diode dynamic parameters

The peak value of the reverse voltage can be found by measuring the diode voltage with a permanent-magnet moving-coil voltmeter reading the r.m.s. value of the voltage. Then the peak value is easily calculated from the following equation:

$$V_p = \sqrt{2}\, V_{r.m.s.} \tag{10}$$

where V_p=peak value of the voltage

$V_{r.m.s.}$=root-mean-square (effective) value of the voltage

It should be noted that equation (10) holds only for voltages of strictly sinusoidal waveform. Thus, at a supply of sinusoidal a.c. voltage the peak value of the reverse voltage can be directly read from the scale of a voltmeter, provided the latter is calibrated in terms of peak values.

A circuit for measuring diode dynamic parameters is presented in Fig. 68. The circuit is energized from the mains through a coupling transformer *Tr*. The functions of the lat-

ter are first of all to ensure the required value of voltage and secondly, to exclude possible interference from the mains. Depending on specified conditions, the transformer may be either a step-up or step-down transformer. Diode D_2 is connected so as to pass the forward current of the diode under measurement and to block its reverse current, while diode D_3 which is oppositely connected to the circuit passes only the reverse current. The forward current is measured by means of ammeter A while the reverse current is read by milliammeter mA.

The reverse voltage amplitude is measured by means of voltmeter V_1. During the half cycle of reverse voltage the entire voltage is applied to the diode because the resistance of all the other circuit elements is infinitely small as compared with the resistance of the diode in the reverse direction.

The forward voltage drop across the diode is measured with the aid of voltmeter V_2. The reverse voltage across the diode does not affect the readings of the voltmeter since the current flows through diode D_4 only during the positive half cycles. The reverse current of diode D_4 should be as small as possible since, combining with the reverse current of the diode TD under test, it may introduce an error into the reverse current I_{rev} being measured. Voltmeter should be calibrated together with the selected diode D_4. Diode D_1 and variable resistor R_1 form a balanced load on the transformer to ensure an undistorted sinusoidal output voltage. This network conducts current during the half cycles of reverse voltage, i.e., when the diode conducts a reverse current of very low value.

During forward voltage drop measurements the required value of current is set by means of variable resistor R_2 and the forward voltage drop is read from the scale of voltmeter V_2.

The function of diode D_5 is to protect voltmeter V_2 against overloads occurring during the half cycles of reverse voltage when the value of the supply voltage applied to the diode across points A and B is many times in excess of the upper limit of the voltmeter range of measurement (it should be remembered that the voltmeter is intended only for measuring the forward voltage drop). It is known that in

a series circuit the voltage across the circuit elements is directly proportional to the resistance of these elements. In the absence of diode D_5 the voltage between points A and B will be:

$$V_{rev} = I_{meas}R_{rev} + I_{meas}R_V \tag{11}$$

where I_{meas}=measurement current flowing through diode D_4 in the reverse direction and voltmeter V_2
R_{rev} =diode resistance in the reverse direction
R_V =internal resistance of the voltmeter

The term $I_{meas}R_{rev}=V_D$ of equation (11) represents the voltage drop across diode D_4 (according to Ohm's law), while $I_{meas}R_V=V_V$ is the voltage drop across the voltmeter V_2. Since R_V and R_{rev} are magnitudes of the same order the voltage drop across the voltmeter V_V is considerable and may damage the instrument.

During the half cycle of reverse voltage diode D_5 is connected in the forward (conducting) direction. The low resistance of this diode shunts the voltmeter and considerably reduces the magnitude of voltage V_V, since almost all the reverse voltage V_{rev} is applied to diode D_4.

After marking the reverse branch of the volt-ampere characteristic curve of the diodes is usually checked once more. This operation is necessary because minute fractures may appear in the crystal as a result of ageing and testing (this will be discussed in greater detail below). Furthermore, the sealing may have been impaired, this leading to condensation of moisture on the crystal. Minute fractures of the crystal cause distortion of the volt-ampere characteristic reverse branch (see Fig. 65*c*).

The reverse branch of the volt-ampere characteristic curve of finished diodes is checked with the aid of the test circuit shown in Fig. 69. This circuit is essentially the same as that used to check the reverse branch of a volt-ampere characteristic curve of a crystal (see Fig. 66), the only difference being that a voltage depending on the type of the tested diode is applied instead of 36 volts as formerly. The horizontal deflecting plates of the oscilloscope are driven by the voltage across resistor R_2 constituting the lower branch of voltage divider R_1-R_2. The magnitude and waveform of this voltage vary by the same law, as the

magnitude and waveform of the reverse voltage applied to points A and B (see Fig. 69). The oscilloscope may be damaged on application of the full reverse voltage, since this voltage may attain hundreds of volts.

Diode D is inserted into the circuit in the direction opposite to that of the diode TD being tested, actually breaking the circuit when the diode TD under test conducts cur-

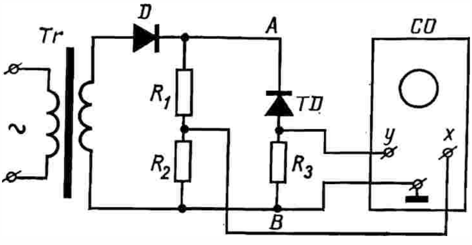


Fig. 69. Circuit for diode volt-ampere characteristic display

rent. As may be seen from the following equation flow of forward current through diode TD would cause a considerable voltage drop across resistor R_3

$$V_R = I_{for} R_3$$

and, consequently, damage the oscilloscope.

It should be noted that the volt-ampere characteristic curves of crystals and finished diodes are also checked, if necessary, during the manufacture of other types of diodes (high-frequency, reference, etc.).

6.3. High-Frequency and Microwave Diodes Measurements

As in the case of rectifier diodes, high-frequency and microwave diodes are subjected to measurement of the maximum reverse voltage at a pre-set value of the reverse current. Besides this, the forward voltage drop at a certain value of forward current is also measured. These are the parameters according to which the diodes are classified.

Among other parameters determining the quality of high-

frequency and microwave diodes the following should be mentioned:

range of operating frequencies Δf;

diode capacitance C;

quality factor Q.

As may be seen from Table 2, these parameters are also measured in manufacture.

The forward voltage drop can be measured in static or dynamic conditions of operation; in the latter case measu-

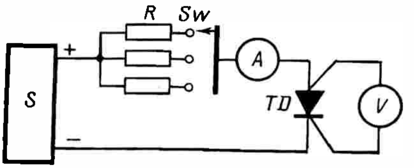


Fig. 70. Circuit for measuring forward branch of volt-ampere characteristics

rements are made in the same way as in the case of rectifier diodes.

In the static conditions of operation the measurements are carried out with the aid of the test circuit shown in Fig. 70. The diode *TD* under test is operated from a d.c. supply source *S* via a resistance box and switch *Sw* (in compliance with the specifications for the given type of diode) this providing the required forward current to be set. The forward voltage drop is measured with voltmeter *V*. The latter is connected directly to the diode leads to eliminate the effect of connecting wires on the voltmeter readings, since their resistance is of the same order of magnitude as that of the diode resistance in the forward direction.

Intermediate measurements of V_{for} of a *p-n* junction can be made only after the terminals have been soldered to it, otherwise the *p-n* junction will inevitably be damaged by the relatively high forward current passing through the points of contact.

The device is considered as having passed the test and fit for service when the forward voltage drop is within specified limits. During classification measurements several different values of the forward current (according to specifications) are set with the aid of switch *Sw* and the corres-

ponding forward voltage drops are measured. The results obtained serve for establishing the type of the diode.

The operation of the diode within a specified frequency range is checked by plotting frequency response according to the data obtained with the aid of the test circuit shown in Fig. 71. The diode *TD* under test (*p-n* junction) operates as a halfwave rectifier of the output signal of a source of sinusoidal voltages *SSV*. The circuit parameters are se-

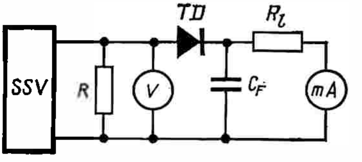


Fig. 71. Circuit for checking operation of diodes within a specified frequency range

SSV—source of sinusoidal voltage; *R*—matching resistor; *V*—peak voltmeter; C_F—filter capacitor; R_l—load resistor

lected so that the diode operates on the section of the volt-ampere characteristic featuring the most pronounced curvature (see Fig. 21) thus ensuring adequate accuracy of the current measurements. This condition is met if the amplitude of the output signal is not above 2 volts, while the total resistance of load R_l and milliammeter *mA* does not exceed 1 kiloohm.

Measurements are carried out in the following way.

The signal source *SSV* is set for operation at the lowest frequency of the specified frequency range. The voltage applied to the diode under test is measured by means of a peak voltmeter *V* and maintained constant throughout the test.

The value of the rectified current is read from the scale of milliammeter *mA* and taken as 100 per cent. The specified frequency range is divided into at least 10 bands and the rectified current is measured at different frequencies of the input signal and reduced to the value obtained from the first measurement.

The diode is considered as having passed the test and fit for service if the rectified current within the specified frequency range is at least 70 per cent of the current measured for the lowest frequency.

Resistor *R* serves as a load for the signal source *SSV* during the voltage half cycles at which the diode is non-conduct-

ing; this is done to avoid distortion of the source output signal. The filter capacitor C_F serves for smoothing the ripple of the voltage rectified by the diode.

The diode capacitance is measured at a fixed frequency by means of the capacitive-resistive voltage divider shown in Fig. 72. The voltage divider is made up of capacitor C and resistor R.

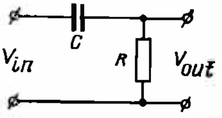


Fig. 72. Capacitive-resistive voltage divider

The reactance of a capacitor is known to be

$$X_C = 1/2\pi fC$$

where f is the frequency of the supplied voltage.

Therefore, the current flowing through the voltage divider will be:

$$I = V_{in}/\sqrt{X_C^2 + R^2} \tag{12}$$

where V_{in} is the input voltage.

Hence, the voltage across the resistor is

$$V_{out} = IR = V_{in}R/\sqrt{(1/2\pi fC)^2 + R^2} \tag{13}$$

where V_{out} is the output signal of the voltage divider.

In cases when $X_C \gg R$ equation (13) may be simplified as follows:

$$V_{out} = V_{in}R/1/2\pi fC = 2\pi fCRV_{in} \tag{14}$$

As can be seen from equation (14), the output voltage V_{out} is, therefore, proportional to the value of capacitance C, i.e., function $V_{out} = f(C)$ is evidently linear.

Figure 73 shows the test circuit used for measuring the diode capacitance by the above-described method.

The capacitive-resistive voltage divider is constituted of resistor R_3 and the capacitance of the diode *TD* being tested. The resistance of R_3 is much lower than the diode capacitive reactance. The sinusoidal output signal from a signal source *SSV* is applied to the voltage divider *TD*-R_3

via a coupling network L_1-L_2, coupling capacitor C_1, and limiting resistor R_1.

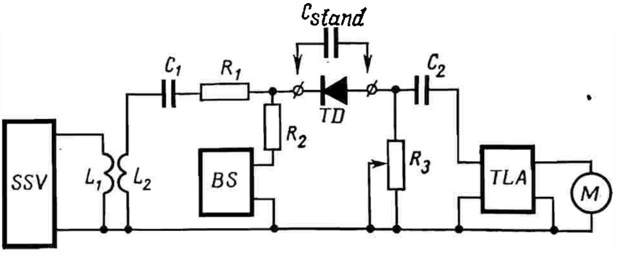


Fig. 73. Circuit for measuring capacitance of semiconductor devices
SSV—source of sinusoidal voltage; L_1 and L_2—coupling network; C_1 and C_2—coupling capacitors; TLA—tuned linear amplifier; M—measuring instrument; BS—source of bias voltage supply; C_{stand}—standard capacitor

A bias voltage source *BS* ensures that the measurements are made on the required section of the diode volt-ampere characteristic curve. The output signal (the voltage drop across resistor R_3) is applied to a tuned linear amplifier *TLA* via a coupling capacitor C_2. This amplifier is a multistage device with a very narrow bandwidth and a linear dependence of the output voltage on the input signal magnitude, hence, its designation. The high selectivity of this amplifier (i.e., its narrow bandwidth) eliminates interference effects at other frequencies. The output high-frequency signal from this amplifier is rectified and supplied to an indicating measuring instrument M (voltmeter) having a uniform scale from which the capacitance is read directly.

Prior to diode capacitance measurements the measuring instrument is calibrated by connecting a standard capacitor C_{stand} instead of the diode. The input signal amplitude and frequency are to be maintained constant throughout the test; varying the amplifier *TLA* gain, the pointer of the indicating instrument is set to correspond to the value of the standard capacitor C_{stand}.

It should be noted that the inherent circuit capacitance should be accounted for during the procedures of calibration and measurement, and the readings of the indicating instrument should be corrected correspondingly.

Diode quality factor measurements are made by the series-tuned circuit method.

Tests are conducted on the test circuit shown in Fig. 74. The tuned circuit is made up of a choke L_{res} and a variable capacitor C_{var} in parallel with the diode TD being tested.

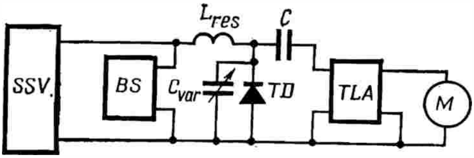


Fig. 74. Circuit for Q-factor measurement

It is known that the voltage across a capacitor in a series-tuned circuit under resonance conditions is:

$$V = V_{in}Q$$

where V_{in} =voltage applied to the circuit
Q=circuit quality factor

The above equation is that of a linear function. A voltage proportional to the circuit quality factor is taken from the circuit formed by the diode being tested and the variable capacitor C_{var}. This voltage is applied to a tuned linear amplifier TLA via coupling capacitor C. The amplifier output is rectified and supplied to a measuring instrument M. The scale of this instrument is graduated directly in terms of equivalent quality factor units (the equivalent quality factor is that of the parallel-connected capacitance of the tested diode and capacitor C_{var}). During measurements the circuit is tuned to resonance by means of the variable capacitor C_{var}, resonance conditions being indicated by maximum readings of the instrument M. Capacitor C_{var} is furnished with a scale, from which the diode capacitance C_D can be directly read off. The values of the inherent quality factor Q_{inh} and inherent circuit capacitance C_{inh} are given in the measuring stand certificate; the quality factor of the diode under test is found from the following equation

$$Q = Q_{inh}Q_{eqv}C_D/C_{inh}\ (Q_{inh} - Q_{eqv}) \tag{15}$$

The Q-factor can also be found from special nomograms if the values of the terms of equation (15) are known.

6.4. Pulse Diode Measurements

The following parameters of pulse diodes are checked in manufacture: $V_{rev.max}$; V_{for}, I_{rev}, $I_{for.max}$. Parameter $V_{rev.max}$ is a classification parameter for diodes of the same type. Beside these, the finished devices are tested for the maximum resistance under pulse conditions $R_{p.max}$ and the time of reverse resistance recovery τ_{off}.

The maximum resistance under pulse conditions is measured with the aid of the test circuit shown in Fig. 75. Rectangular

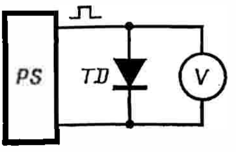


Fig. 75. Circuit for measuring maximum resistance of pulse diodes

pulses supplied by pulse source *PS* are applied to the diode *TD* under test, pulse polarity corresponding to the conducting direction of the diode. The pulse source is a supply of pulse voltage with a high internal resistance. Therefore, the current through the diode does not exceed rated value despite the low forward resistance of the diode. Limiting the diode current in the usual way, i.e., by means of a series resistor, would cause pulse pattern distortions due to an increased time constant of the load presented to the pulse source. The magnitude of the current pulse through the diode is determined by the pulse source and is independent of the type of diode being tested, since—under pulse conditions—the internal resistance of the source is much higher than that of the diode.

The forward voltage drop across the diode is measured by pulse voltmeter *V*.

Under pulse conditions the maximum diode resistance is calculated from equation

$$R_{p.max} = V_{for.p.max}/I_p \tag{16}$$

where $V_{for.p.max}$=maximum forward voltage drop under pulse conditions

I_p=current pulse

The diode is considered as having passed the test if the resistance lies within the range of specified values.

The time of reverse resistance recovery is measured by means of the test circuit shown in Fig. 76. The diode *TD* under test is supplied with a forward current from a d.c. supply source *S* via a limiting resistor R_1. Simultaneously, a pulse of reverse voltage derived from a rectangular pulse source *PS* is applied to the diode. The recovery time τ_{off}

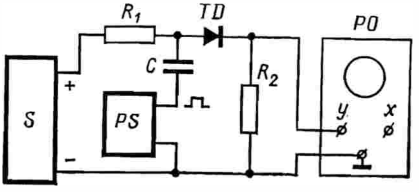


Fig. 76. Circuit for measuring time of reverse resistance recovery of pulse diodes

i.e., the time interval between the moment of disappearance of the diode current and the moment when the diode reverse current drops to a prescribed value (see Fig. 26), is measured by means of a pulse oscilloscope *PO* driven by the voltage across resistor R_2, this voltage drop being proportional to the diode current.

Coupling capacitor *C* eliminates the effect of the pulse source on the current delivered by the d.c. supply. This capacitor has an infinitely great d.c. resistance and prevents the direct current from passing to the pulse source *PS*.

The d.c. supply source *S* should be of sufficiently high internal resistance to avoid pulse pattern distortions, in other words, to prevent a.c. shunting of the diode.

6.5. Reference Diode Measurements

As may be seen from Table 2, the following parameters of reference diodes are to be measured: V_{for}, $V_{rev.\max}$, I_{rev}, $I_{for.\max}$; besides these, the classification parameters, stabilization voltage V_{st} and differential resistance R_d at a predetermined value of the stabilization current, are measured.

The first four parameters are tested in the same way as those of rectifier diodes. Measurements of rectifier and re-

ference diodes differ in that the former are classified into types on completion of the manufacturing process, whereas the latter are classified at the very first stages of the manufacturing process. In fact, the wafers with *p-n* junctions are already subject to classification. By choosing a specific grade of silicon and strictly adhering to the technological procedure of thermodiffusion processing it is possible to obtain *p-n* junctions of parameters corresponding to those of a definite type of diode.

The parameters of reference diodes are measured both on *p-n* junction crystals (intermediate measurements) and the

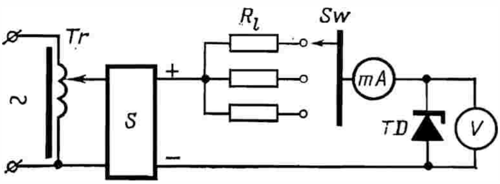


Fig. 77. Circuit for measuring stabilization voltage of reference diodes

finished devices. The latter are classified according to the specified value of the stabilization voltage.

The stabilization voltage is measured by means of the test circuit shown in Fig. 77. The voltage of the d.c. supply source S can be varied with the aid of autotransformer Tr; the current passed through the diode TD under test is set to required value by means of a resistance box R_l and measured by milliammeter mA. The stabilization voltage is read directly from the scale of voltmeter V.

The differential resistance of a reference diode is defined as the ratio of the change in the stabilization voltage to infinitely small variations of the stabilization current. It is almost impossible to determine the differential resistance by measuring the change in the stabilization voltage on direct current, since this change is negligible as compared to the value of the stabilization voltage.

When measuring the differential resistance the usual practice is to superimpose the stabilization current a.c. component on its d.c. counterpart. This causes an a.c. com-

ponent to arise in the stabilization voltage; its magnitude being determined from Ohm's law:

$$\Delta V_{st} = \Delta I_{st} R_d$$

where ΔI_{st} =stabilization current a.c. component
R_d=diode differential resistance

This stabilization voltage a.c. component can easily be measured with the aid of an a.c. millivoltmeter, since this meter does not response to the d.c. voltage component and measures only the absolute magnitude of the a.c. compo-

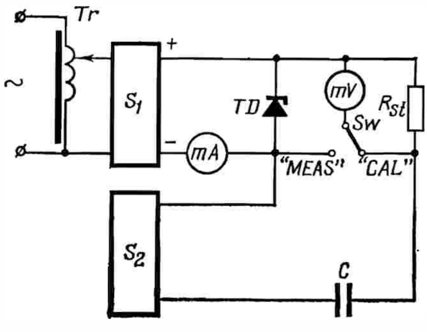


Fig. 78. Circuit for measuring differential resistance of reference diodes

nent. Thus, the differential resistance can easily be found by measuring the stabilization voltage a.c. component at a given value of the a.c. current component.

The circuit used to measure the differential resistance of reference diodes is shown in Fig. 78. The diode *TD* under test is connected to an adjustable supply source S_1 of d.c. voltage and the stabilization current is measured by milliammeter *mA*.

The a.c. current component through diode *D* is provided by an a.c. supply source S_2; this current flows along the following path: supply source S_2—capacitor *C*—resistor R_{st}—diode *TD*—supply source S_2. The coupling capacitor *C* prevents the d.c. current from passing through supply source S_2 and thus eliminates its effect on the accuracy of measurements. The internal resistance of supply source S_1 should be as high as possible so as not to shunt the diode under measurement for alternating current.

Measurements are carried out in the following way. Switch Sw is set in the calibration position and the a.c. voltage component across a standard resistor R_{stand} is read from the scale of millivoltmeter mV. Then the a.c. current component through the diode being tested is calculated from these readings:

$$\Delta I_D = V_R / R_{st} \tag{17}$$

The switch is then set in the measurement positon and the same millivoltmeter mV is used to measure the a.c. voltage component ΔV_D across the diode being tested.

The differential resistance of the diode is then calculated as follows:

$$R_d = \Delta V_D / \Delta I_D$$

If the same a.c. component value is adopted for all these measurements, the scale of millivoltmeter mV may be graduated directly in ohms.

6.6. Switching Diode Measurements

With switching diodes (controlled, as well as uncontrolled) the manufacturing cycle includes the measurement of the following parameters (see Table 2):

switching voltage V_{sw};
switching current I_{sw};
cutoff current I_{cutoff};
residual voltage V_{res};
leakage current I_{leak};
maximum forward current $I_{for.\max}$;
maximum reverse voltage $V_{rev.\max}$;
reverse current I_{rev};
maximum forward voltage $V_{for.\max}$.

Besides this, controlled diodes are tested for the values of control current I_{con} and control voltage V_{con}.

As with other diode types, the volt-ampere characteristic of the p-n junction is measured, and, if necessary, that of the finished switching diode.

At the laboratory stage the switching-on time t_{on} and the switching-off time t_{off} are measured on several samples of every batch of controlled switching diodes.

The classification parameters of switching diodes are V_{sw}, $V_{for.max}$, and $V_{rev.max}$, the last two being obligatory only for certain diode types.

Surveying the volt-ampere characteristics of switching diodes is accomplished with the aid of an oscilloscope equipped with a special contrivance (Fig. 79).

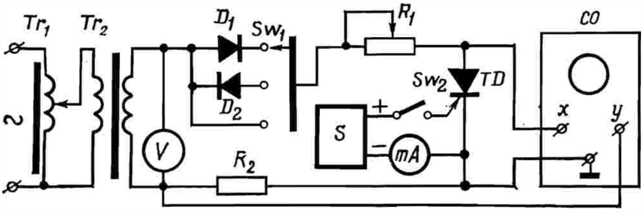


Fig. 79. Circuit for displaying volt-ampere characteristics of switching diodes

A voltage supply source consisting of an autotransformer Tr_1, coupling transformer Tr_2, and auxiliary diodes D_1 and D_2 provides a halfwave voltage waveform. The amplitude of this voltage is varied by means of the autotransformer Tr_1 and measured by voltmeter V.

With switch Sw_1 in the upper position the forward branch of the volt-ampere characteristic is displayed on the oscilloscope screen, in the middle position, the reverse branch, and in the lower position, both the forward and reverse branches simultaneously, i.e., the complete volt-ampere characteristic.

The voltage across the diode under test is applied to the terminal x of the oscilloscope, while the terminal y is driven by the voltage across resistor R_2; the voltage is proportional to the current passed through the diode.

When volt-ampere characteristics of controlled diodes are surveyed, the control electrode is driven from a stabilized adjustable voltage supply source S. The control current is measured by a milliammeter mA. After closing switch Sw_2 the control current is set to the required value. The volt-ampere characteristic is surveyed with a gradually increasing voltage at the autotransformer Tr_1 output. The

switching diode is considered as having passed the test if the switching takes place with diode voltage and control current within the specified limits. In this case the so-called "rectified" volt-ampere characteristic (see Fig. 29) is displayed on the oscilloscope screen.

When volt-ampere characteristics of uncontrolled switching diodes are checked, the stabilized voltage supply source S is omitted.

The circuit of Fig. 79 makes it possible to survey the volt-ampere characteristics of crystals (in fittings, as well as without them) along with those of finished diodes.

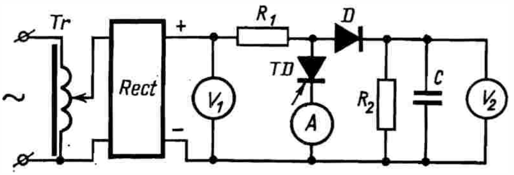


Fig. 80. Circuit for measuring switching voltage and current of switching diodes

Switching voltage and current are measured by means of a circuit shown in Fig. 80. The voltage from the output of a halfwave rectifier *Rect*, that can be varied by means of an autotransformer *Tr*, is applied to the diode *TD* under test via a limiting resistor R_1. The voltage is measured by a voltmeter V_1. Diode switching will take place if the amplitude of the applied voltage is at least equal to the switching voltage. The moment when switching takes place is indicated by an ammeter A: the readings of this ammeter will drop abruptly after the voltage amplitude has exceeded the value of V_{sw}.

Figure 81 presents a simplified version of the pattern of the voltage across a switching diode fed by a halfwave voltage. As can be noted, the presence of a switching diode causes the formation of pulses with an amplitude equal to V_{sw}.

The pulse amplitudes are measured with the aid of a diode peak voltmeter (Fig. 80), consisting of a diode D, resis-

tor R_2, capacitor C, and voltmeter V_2. Measurements are carried out on finished switching diodes. According to the results of these measurements the diodes can be referred to one or another type of construction.

Cutoff current of controlled diodes can be measured with a circuit shown in Fig. 82.

A push-button switch *BSw* closes the circuit and a control current is fed to the diode *TD* under test. This current

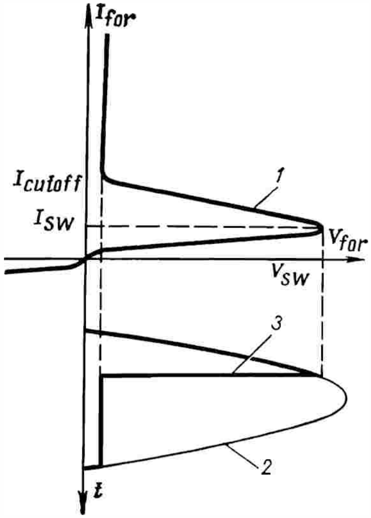


Fig. 81. Simplified waveform of the pulse generated across a switching diode with halfwave voltage applied

1—volt-ampere characteristic of switching diode; *2*—applied voltage; *3*—developed voltage pulse

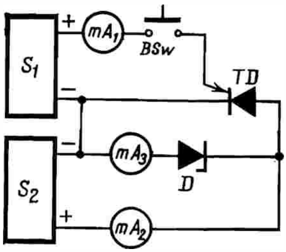


Fig. 82. Circuit for measuring cutoff current of switching diodes

is provided by a d.c. supply source S_1 and measured by a milliammeter mA_1. The diode is operated from a supply source S_2 of stabilized d.c. voltage. A circuit branch composed of milliammeter mA_3 and reference diode D is connected in parallel to the diode *TD* being tested.

Measurements are made in the following order. Depressing the push-button switch closes the circuit and diode *TD* is switched on; after this the switch is released, thus breaking the circuit. The output voltage of supply source S_2 is gradually reduced till the readings of milliammeter mA_3 do not abruptly rise; at this moment all further reduction in voltage is ceased and the cutoff current value is read from the milliammeter mA_2 scale.

During measurements the circuit operates as follows. When diode *TD* being tested is switched off the voltage across it sharply increases, thus causing reference diode *D* to conduct current abruptly. Now, the current from d.c. supply source S_2 mainly flows through the reference diode. Since the resistance of a conducting reference diode is about the same as of a switching diode in the switched-on state and supply source S_2 is provided with current stabilization facilities, the current in the circuit during switching remains practically constant.

Any indicating device with a control current equal to or in excess of the measuring circuit current can be used instead of a milliammeter.

The measurement method described can be used to measure the cutoff current of uncontrolled diodes, too. In this case the diode under test is switched on by applying a voltage equal to V_{sw} to it and switched off by reducing the magnitude of the applied voltage.

The value of the control current may be tested in intermediate measurements, as well as on the finished diode, depending on the manufacture conditions.

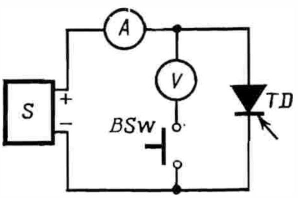


Fig. 83. Circuit for measuring residual voltage across switching diodes

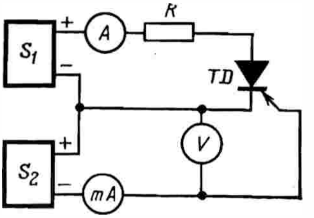


Fig. 84. Circuit for measuring control current and voltage of controlled diodes

Residual voltage is measured by means of a circuit shown in Fig. 83. The diode *TD* being tested (controlled or uncontrolled) is powered from an adjustable stabilized supply source *S* of d.c. voltage. During measurements the diode is switched on (for the sake of simplicity the switching net-

work is omitted from this circuit diagram) and the diode current is set to a predetermined value by means of varying the supply voltage. The diode current is measured by ammeter A. After this switch is closed and the residual voltage value is read from the voltmeter V scale.

The switch BSw should in no case be closed when the diode is switched off, since in this case the voltage drop across the diode is considerable and voltmeter V can be damaged.

As a rule, the residual voltage test is performed only to check finished devices.

The leakage current, maximum forward current, reverse current, reverse voltage, and maximum forward voltage are measured by the same techniques as described above.

The control current and voltage of controlled diodes are measured with the aid of a circuit presented in Fig. 84. A d.c. voltage supply source S_1 provides the voltage for the diode TD being tested, while a d.c. voltage supply source S_2 generates the control voltage. Switching the diode under test is produced by gradually increasing the control current, the moment of diode switching being indicated by a rapid change in the readings of ammeter A. The control voltage and control current are read from the scales of voltmeter V and milliammeter mA, respectively, at the moment of diode switching-on. The device is considered as having passed the test if values of I_{con} and V_{con} are within limits stipulated in the specifications. These parameters are measured when finished diodes are tested.

6.7. Transistor Measurements

Transistors, just the same as diodes, are classified according to their classification parameters. Classification parameters are listed in transistor specifications. For instance, low-power low- and medium-frequency transistors are classified by the value of the current-amplification factor and the limiting frequency of current amplification or oscillation; low-power high-frequency transistors are classified by the static current-amplification factor in the common-emitter circuit and the modulus of this current-amplification factor at a frequency from 10 to 20 megahertzes; high-power low-frequency transistors are classified by the

maximum permissible reverse collector-base voltage and the static current-amplification factor in the common-emitter circuit.

In certain transistor types other classification parameters are adopted.

During the transistor manufacture intermediate measurements of the devices are carried out. As a rule, classification and intermediate measurements are made in one and the same way. The following main transistor parameters are measured:

collector and emitter reverse currents $I_{c.rev}$ and $I_{e.rev}$;
output admittance h_{22};
alpha-cutoff frequency f_{α};
modulus of the current-amplification factor $|\beta|$;
maximum oscillation frequency f_{max};
transistor noise factor K_n;
forward transfer admittance g_{stat};
saturation collector voltage $V_{c.sat}$ and saturation base voltage $V_{b.sat}$;
time constant $r'_b C_c$ of the feedback;
collector and emitter junction capacitances.

Transistor characteristics are displayed in the same way as diode characteristics by means of the methods discussed earlier.

Transistor parameters measured during manufacture are listed in Table 2 for various transistor types.

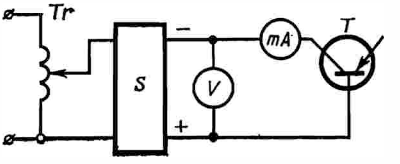


Fig. 85. Circuit for collector reverse current measurements

The collector reverse current $I_{c.rev}$ is measured with the aid of a circuit shown in Fig. 85. The collector-base junction of transistor T under test is supplied from a d.c. voltage supply source S with a reverse voltage,* whose magnitude is controlled by voltmeter V. The magnitude of the

* In measuring circuits here and further the polarity of voltage and current is indicated for transistors of p-n-p type. When n-p-n transistors are measured, the polarity should be reverse.

reverse current is measured with the aid of milliammeter *mA* at a voltage stipulated in the type specifications.

The emitter reverse current $I_{e\,rev}$ can be measured by the same method. In this case the reverse voltage is applied to the emitter-base junction of the transistor under test.

The tested transistor is considered as fit for service if the collector (emitter) reverse current is within specified limits.

The output admittance h_{22} is measured with the input circuit under no-load conditions; the measurements are

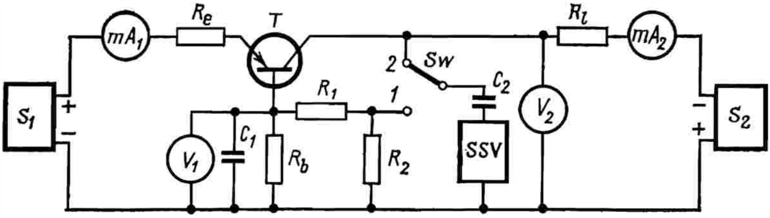


Fig. 86. Circuit for output admittance measurements

made with a sinusoidal current of 50-1,000-hertz frequency. The circuit used for output admittance measurements is shown in Fig. 86. The transistor *T* under test has a common-base connection. The d.c. operating conditions are indicated by milliammeters mA_1, mA_2, and voltmeter V_2 and are set by varying the output voltages of d.c. supply sources S_1 and S_2. The output admittance is found as:

$$h_{22} = I_c/V_{c.b}$$

where I_c=a.c. component of the collector current

$V_{c.b}$ =a.c. voltage across the collector-base junction

The $V_{c.b}$ voltage is supplied from the source of sinusoidal voltage *SSV* with switch *Sw* in position *1* and is measured by a valve voltmeter V_1 with the aid of divider R_b-R_1. The voltmeter indicates the voltage across resistor R_b, this voltage being a component of the output voltage V_{out} of source *SSV*:

$$V_1 = V_{out}R_b/(R_b + R_1) \tag{18}$$

where V_{out} is the output voltage of source *SSV* measured after coupling capacitor C_2.

Then switch *Sw* is set in position *2* in order to measure the voltage V_2 across resistor R_b. The collector current I_c can be found as:

$$I_c = V_2/R_b \tag{19}$$

The output voltage V_{out} of source *SSV* is maintained at a constant level, irrespective of the position of switch *Sw*. If the value of resistor R_b is selected so that $R_b \leqslant 1/100\ h_{22}$, $V_{c.b}$ will almost be equal to the output voltage V_{out} of source *SSV*. In this case it follows from equation (18) that

$$V_1 = V_{c.b}R_b/(R_b + R_1) \tag{20}$$

Assuming $R_1 \ll R_b$ from equation (20) we get

$$V_{c.b} \approx V_1R_1/R_b \tag{21}$$

Finally, substituting equations (19) and (21) into the equation for h_{22} we get:

$$h_{22} \approx V_2/V_1R_1 \tag{22}$$

From equation (22) it follows that the function $h_{22} = f(V_2)$ is linear when V_1=const. Therefore, the scale of voltmeter V_1 can be calibrated directly in units reciprocal to the output admittance. Capacitor C_1 bypasses the base currents to earth, thus eliminating the possibility of circuit self-excitation.

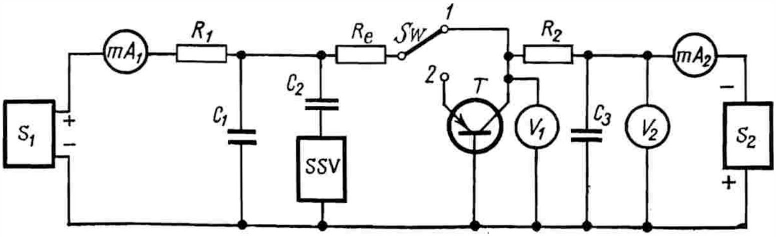


Fig. 87. Circuit for alpha-cutoff frequency measurements

Alpha-cutoff frequency f_α is measured with the aid of the circuit shown in Fig. 87. The transistor under test has

a common-base connection. The emitter current is set by a d.c. voltage supply source S_1 via resistors R_1 and R_e and is measured by milliammeter mA_1. The collector voltage is derived from another d.c. voltage supply source S_2 and is applied to the collector via resistor R_2.

The alpha-cutoff frequency is determined by measuring the modulus of the current-amplification factor (α), the latter being defined as the ratio of the a.c. component of the collector I_c to the emitter a.c. component I_e.

Setting switch *Sw* in position *1* closes the circuit and an a.c. signal from a source of sinusoidal voltage *SSV* is applied to the load resistor R_2 via coupling capacitor C_2 and resistor R_e. The a.c. voltage across resistor R_2 is measured by voltmeter V_1 (the a.c. voltage across the coupling capacitor C_3 can be neglected). In this case

$$I_e = V_1/R_2$$

where V_1 is the a.c. voltage drop.

Switch *Sw* is set in position *2* and the output current of source *SSV* is applied to the emitter circuit. The magnitude of the current remains constant due to

$$R_{SSV} \gg R_2 \text{ and } R_{SSV} \gg h_{11}$$

where R_{SSV} = internal resistance of source *SSV*
h_{11} = input resistance of the transistor (the resistance of the emitter-base junction)

The collector current produces a voltage drop across resistor R_2 that is indicated by voltmeter V_1. Therefore

$$I_c = V_2/R_2$$

where V_2 is the a.c. voltage drop across R_2.

By definition the current-amplification factor

$$|\alpha| = I_c/I_e \text{ or } |\alpha| = V_2/V_1 \tag{23}$$

These measurements are made several times at various frequencies of the signal from source *SSV*.

The frequency, at which the value of $|\alpha|$ drops to 0.7 is termed the alpha-cutoff frequency f_α. From equation (23) it follows that the scale of voltmeter V_1 can be calibrated directly in units of the modulus $|\alpha|$ if V_1=const.

Modulus of the current-amplification factor $|\beta|$ is mea-

sured at a high frequency in the circuit presented in Fig. 88. The transistor T under test is inserted in the common-emitter circuit relative to alternating current and common-base circuit relative to direct current. The d.c. operating conditions are provided by d.c. voltage supply sources S_1 and S_2. The high-frequency signal is generated by signal source SS and is applied to the transistor emitter circuit via coupling capacitor C_3.

Coupling capacitors C_1 and C_2 bypass a.c. components of supply sources S_1 and S_2, respectively.

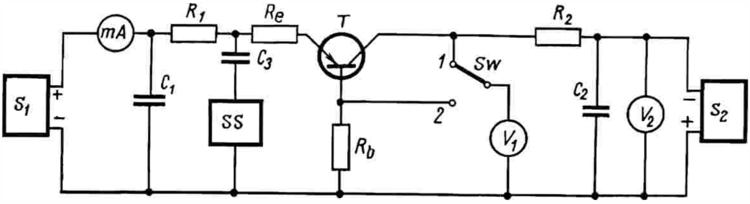


Fig. 88. Circuit for measuring modulus of the current-amplification factor

With switch Sw set in position *1* the valve voltmeter V_1 measures the voltage drop across resistor R_2 equal to:

$$V_1 = I_c R_2 \tag{24}$$

where I_c is the a.c. component of the collector current.

When the switch is set in position *2* the readings of voltmeter V_1 correspond to the voltage drop V_2 across the base resistor R_b. The values of the circuit elements are selected so as to provide the practical independence of transistor operating conditions from the position of switch Sw.

$$V_2 = I_b R_b$$

where I_b is the a.c. component of the base current.

The current-amplification factor modulus is therefore:

$$|\beta| = I_c/I_b \text{ or } |\beta| = V_1 R_b / V_2 R_2 \tag{25}$$

With V_2 being maintained constant throughout the entire measurement cycle the scale of voltmeter V_1 can obviously be calibrated directly in $|\beta|$ units.

Maximum oscillation frequency f_{max} is measured in an oscillator circuit (Fig. 89). The collector voltage of the transistor T under test is provided by a d.c. voltage supply source S and applied to the collector via limiting resistor R. Oscillations in this circuit can be induced by applying a feedback voltage from the collector to the emitter via capacitor C_1. The oscillation frequency is determined by the

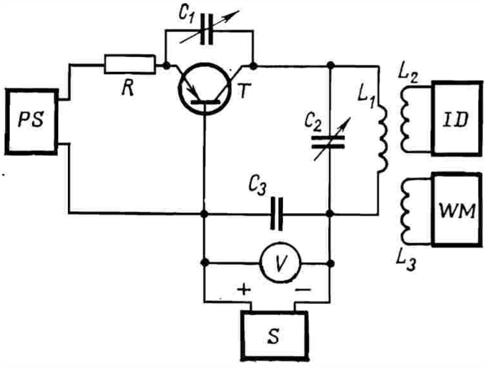


Fig. 89. Circuit for maximum oscillation frequency measurements

well known equation acquiring in this case the following form:

$$f_{max} = 1/2\pi\sqrt{L_{eqv}C_2} \tag{26}$$

where L_{eqv}=equivalent inductance of tuned circuit C_2-L_1-L_2-L_3

C_2 =capacitance value

During measurements the value of C_2 is reduced till oscillations in this circuit cease. A lower value of C_2 corresponds to a higher oscillation frequency in accordance with equation (26). The circuit is again self-excited by increasing the capacitance of C_1, then again cut off by reducing the capacitance of C_2, and so on till finally no increase in C_1 is capable of inducing self-excited oscillations.

The maximum frequency at which oscillations can yet be detected is known as the maximum oscillation frequency f_{max}. Frequency measurements are made by means of a frequency meter (wavemeter) WM. The presence of oscilla-

tions in the circuit is indicated by an indicating device *ID*. The oscillations are pulse modulated to improve the sensitivity of the measuring instruments; this is achieved by means of a pulse modulator in the emitter circuit of the transistor. The maximum oscillation frequency is used as a classification parameter for certain types of high-frequency transistors.

Transistor noise factor K_n of a transistor is measured at frequencies of 1,000 hertzes by a method according to which

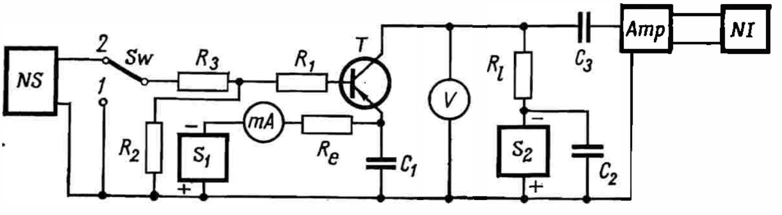


Fig. 90. Circuit for noise factor measurements

the input external noise power required to produce a twofold increase in the output noise (as compared to the case of a short-circuited input) is measured. This is shown in Fig. 90.

D.c. voltage supply sources S_1 and S_2 provide the operating conditions of transistor T under test in accordance with the specifications. The base voltage is developed by a voltage divider R_3-R_2 and applied to the transistor base via resistor R_1. D.c. operating conditions of transistors are indicated by meters *mA* and *V*.

First, the level of output noise power delivered to load resistor R_l is measured with switch *Sw* set in position *1*; this power level is indicated by means of a noise indicator *NI* driven by a tuned amplifier *Amp*. After this a noise source *NS* is connected to the transistor input by setting switch *Sw* in position *2*.

The output level of the e.m.f. of this source is gradually increased till the readings of the noise indicator do not increase by a factor of two (as compared to those taken with switch *Sw* in position *1*). The noise factor is then read from

a calibrated scale on the output level control of the noise source.

The transistor under test is considered to be fit if the noise factor does not exceed limits listed in the type specifications.

Bypassing capacitors C_1 and C_2 shunt d.c. supplies S_1 and S_2, respectively, relative to the a.c. components of emitter and collector currents.

Forward transfer admittance measurements are carried out in the common-emitter circuit of the transistor under test, as illustrated in Fig. 91. Proper operating conditions

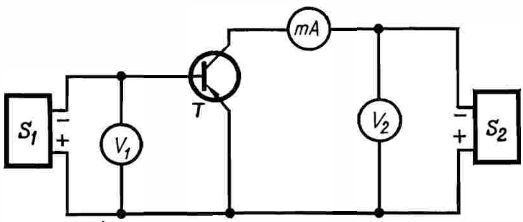


Fig. 91. Circuit for forward transfer admittance measurements

are provided by d.c. voltage supply sources S_1 and S_2 and are measured by voltmeters V_1 and V_2 and milliammeter mA.

The output voltage of S_1 is increased so as to ensure a certain value of collector current I_c in accordance with the type specifications of the transistor under test.

The forward transfer admittance is

$$g_{stat} = I_c/V_b$$

where V_b is the base voltage.

Saturation voltage is tested in the common-emitter circuit (Fig. 92). A base current I_b from an adjustable source S_1 of d.c. voltage supply is fed to the base of transistor T under measurement via resistor R_1. The magnitude of this current is measured by milliammeter mA_1. The transistor collector voltage is supplied by a d.c. voltage supply source S_2 and the collector current is set by the readings of milliam-

meter mA_2. The base and collector currents are stabilized by means of resistors R_1 and R_2, respectively, currents being independent from the parameters of the transistor under test.

The base saturation current is set so as to meet the condition

$$I_b = (2\text{-}5)\ I_c/\beta_{stat}$$

where β_{stat} is the maximum value of the static current-amplification factor in the common-emitter circuit for the type of transistors under measurement.

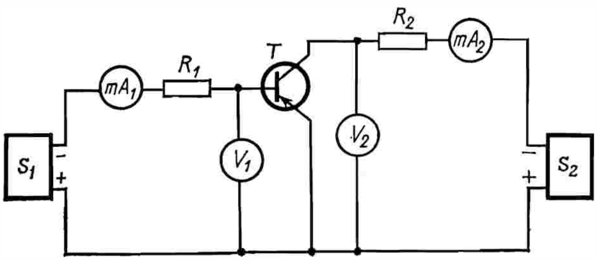


Fig. 92. Circuit for saturation voltage measurements

Under saturation conditions two parameters are measured: the base saturation voltage $V_{b.sat}$ and the collector saturation voltage $V_{c.sat}$, both being measured by voltmeters V_1 and V_2, respectively. The transistor is considered as having passed the test if both parameters measured do not exceed limits stipulated in the specifications.

Time constant r'_bC_c *of the feedback* is measured only for high-frequency transistors. These measurements are made usually at a frequency of 5 megahertzes (unless otherwise specified) with the aid of a circuit shown in Fig. 93. The d.c. operating conditions of transistor T under test are set by d.c. voltage supply sources S_1 and S_2, resistor R_e in the emitter circuit serves to stabilize the emitter current. The voltage at a frequency f is applied to the collector by the source of sinusoidal voltage SSV via capacitor C_1. The emitter-base voltage $V_{e.b}$ (that is measured by means of a valve voltmeter V_1) is proportional to the amount of internal feedback with time constant r'_bC_c.

The value of the time constant of the internal feedback $r'_b C_c$ is measured by comparing the readings of voltmeter V_1 taken with the transistor under test switched on with those when the transistor is replaced by an equivalent standard network $R_{st}C_{st}$. The voltmeter scale can be calibrated directly in corresponding time units by means of standard networks with various values of the product RC. The circuit C_2-L is tuned to the frequency of source *SSV* and pro-

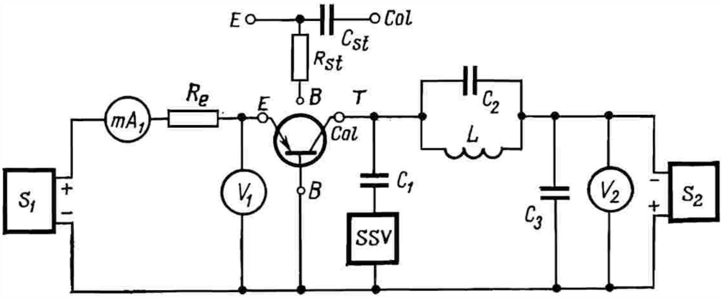


Fig. 93. Circuit for measuring time constant of transistor feedback

vides the required degree of decoupling of the latter from the d.c. supply. The output signal of source *SSV* should be maintained constant throughout the measurements of the transistor and the standard network. The transistor is considered as having passed the test if the time constant of the internal feedback is within the limits stipulated in the specifications.

This time constant is used as a classification parameter for certain types of high-frequency transistors.

Collector and emitter junction capacitances are measured in much the same way as described in Sec. 6.6. of this Chapter.

6.8. Measurements of Varicap Diodes, Tunnel Diodes, Photodiodes, Phototransistors, and Photoresistors

The following parameters are measured during the manufacture of *varicap (varactor) diodes*:

rated capacitance C_{rated} at a specified bias voltage;
maximum bias voltage $V_{bias\ max}$;

quality factor Q at a specified frequency and bias voltage.

Beside these, intermediate measurements of the reverse current I_{rev} are carried out. Varicap parameters depend on the ambient temperature to a great extent, that's why the admissible variations of the temperature are stipulated in the specifications.

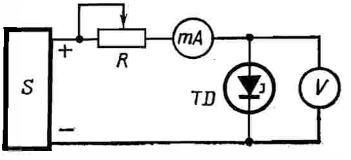
The capacitance and quality factor of varicap diodes are measured with the same methods as described in Sec. 6.6.

The capacitance variation factor is

$$k = C_{\max}/C_{\min}$$

where $C_{\max}$ and $C_{\min}$ are the varicap diode capacitances at the maximum and minimum bias voltage (absolute values), respectively.

Fig. 94. Circuit for plotting tunnel diode volt-ampere characteristics



The maximum bias voltage is measured with the varicap diode connected to a circuit for examination of the reverse branch of the volt-ampere characteristic of rectifier diodes (see Fig. 67).

Tunnel (Esaki) diodes are classified according to the following parameters (see Fig. 30):

maximum (peak) current $I_{\max}$;

diode capacitance C.

While measuring the maximum current the corresponding voltage V_{peak} is measured as well.

Maximum current measurements are made with the aid of a circuit for plotting a diode volt-ampere characteristic (Fig. 94). A variable resistor R is used to gradually increase the current through the diode TD under test, till the voltage across the diode does not drop abruptly from V_{peak} to $V_{\max}$. The value of the current measured at this abrupt change by milliammeter mA is equal to the maximum current $I_{\max}$.

The tunnel diode capacitance is measured in much the same way as that of high-frequency diodes. The volt-ampere characteristic (that is, the diode capacitance as a function of the bias voltage) can be plotted point-by-point by varying the bias voltage (see Fig. 73) applied to the diode *TD*. Tunnel diode capacitance is usually measured at a bias voltage corresponding to the valley of the characteristic (i.e., at V_{val}). With the quiescent point selected in such a way, any change in the voltage will result in an increase in the diode current, irrespective of whether the voltage is lower or higher (a detailed description of this effect is beyond the scope of the present discussion).

The quality of tunnel diode operation is often evaluated by its switching time t_{sw}, i.e., the time required for a diode to change from a state corresponding to V_{max} to a state corresponding to V_{val}. This switching time depends on the circuit in which the diode is employed, as well as on the diode parameters. The switching time t_{sw} is the lower (the diode is of a higher quality) the lower is the ratio C/I_{max}.

Modern tunnel diodes feature switching time of the order of 10^{-9} s. Measuring such short time intervals is rather a complicated problem and in mass-scale production such measurements are usually not made.

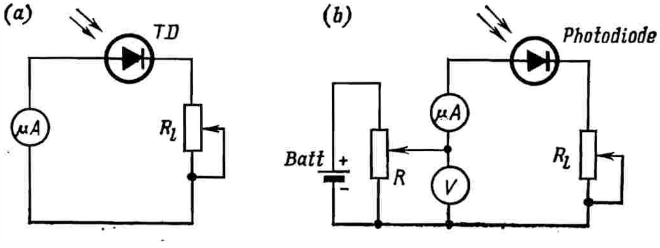


Fig. 95. Circuits for measuring photodiode parameters
(*a*) without external voltage supply; (*b*) with external voltage supply

Photodiodes are utilized (and, therefore, tested) under two kinds of operating conditions:

as a key, without an external voltage supply (Fig. 95*a*);
as a diode, with an external voltage supply (Fig. 95*b*).

In the key mode of operation photodiode circuits feature a low level of inherent noise and the absence of dark currents, but at the same time the magnitude of the generated e.m.f. is very low.

In the diode mode of operation the signal current (i.e., current under illumination) is 2-3 times higher than in the key mode of operation, but then a dark current is present and the noise level is also considerably higher.

The circuit presented in Fig. 95*a* provides the measurement of two diode parameters: the dark current I_d and the signal current I_s. Two volt-ampere characteristics can be plotted with the aid of the circuit shown in Fig. 95*b*: without diode illumination (the dark volt-ampere characteristic) and at a certain level of incident illumination (the signal volt-ampere characteristic).

Phototransistors are connected into the measuring circuit as diodes, i.e., the voltage is applied between the collector and emitter and no external voltage is applied to the base (the measuring circuit is similar to that of Fig. 95). Usually two characteristics, as in the case of photodiodes, are measured.

Photoresistors (photovaristors) are tested in the same way as photodiodes: two volt-ampere characteristics (the dark and signal volt-ampere characteristics) are plotted with the aid of a circuit shown in Fig. 95*b*.

6.9. Laser Diode Measurements

Semiconductor optical oscillators utilizing quantum-mechanical effects, i.e., laser diodes, are evaluated, as mentioned earlier, by their output power (intensity of radiation) P_{rad}, density of excitation (pumping) current I_{pump}, and radiation spectrum (intensity of radiation as a function of the optical wavelength) $P_{rad}=f(\lambda)$.

The intensity of light radiation is measured with the aid of the circuit shown in Fig. 96. A pulse source *PS* generates rectangular current pulses of very short duration (a few microseconds) and operates synchronously with the master timer of the circuit. These pulses drive the so-called pumping current source *PCS* which is designed to provide pulses of very high power levels with minimum pulse

pattern distortions. The laser diode *LD* under test is connected to source *PCS* in the conducting direction and draws very heavy pulse currents (up to scores and even hundreds of amperes). These heavy current pulses cause diode excitation, i.e., produce radiation of pulses of light.

A voltage proportional to the magnitude of the current pulse is developed across resistor R_1 and measured by pulse voltmeter V_1.

The pulses of light radiated by the laser diode are detected by a photodiode.

A voltage supply source *Batt* provides a bias voltage that cuts the photodiode off. Since the resistance of this

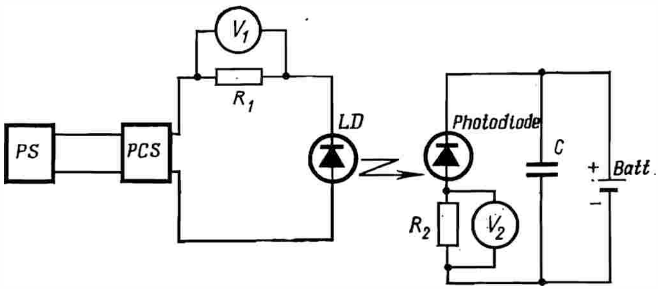


Fig. 96. Circuit for measuring intensity of radiation of laser diodes

diode is in inverse proportion to the intensity of its illumination, the current pulse generated in the circuit of this diode will be proportional to the level of incident illumination. As a result, the voltage developed by the current pulse across resistor R_2 will be proportional to the intensity of laser diode *LD* radiation. This voltage is measured by pulse voltmeter V_2 which has a scale calibrated directly in intensity units. In this way the output power of the laser diode is measured.

Capacitor *C* shunts the bias voltage supply source *Batt* relative to a.c., presenting a very low reactance to short pulse currents.

With a given pumping current and area of *p-n* junction the density of the pumping current can easily be determined as

$$\psi_{pump} = I_{pump}/A$$

where I_{pump} = value of the pumping current
A = area of the p-n junction

The radiation spectrum of a laser diode is measured by means of an installation, whose block-diagram is presented in Fig. 97. The laser diode *LD* under test is mounted in front of the input optical system of a spectrograph *SG*, whose function is to extract oscillations of a specified wavelength from the total beam of light at its input. A pulse

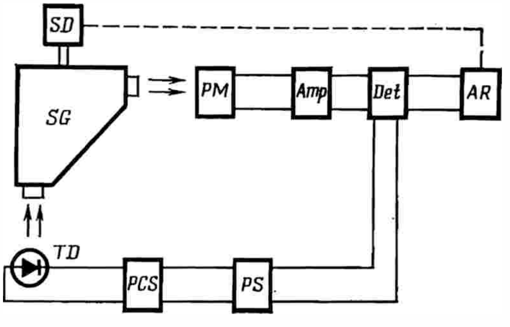


Fig. 97. Block-diagram of installation for measuring radiation spectrum of laser diodes

SD—synchrodrive; *SG*—spectrograph; *PCS*—pump current source; *PS*—pulse source; *PM*—photomultiplier; *Amp*—selective amplifier; *Det*—synchronous detector; *AR*—automatic recorder

source *PS* causes diode excitation by means of pump current source *PCS* and acts as the master timer of the entire installation. The pulses of light produced at the spectrograph output are converted into current pulses in photomultiplier *PM*. The output signal of the photomultiplier is amplified in a tuned (selective) amplifier *Amp* and applied to synchronous detector *Det*. The detector *Det* is cut off all the time between adjacent pulses, this providing a higher precision of measurements due to a lower level of interference at the system output in pauses between pulses. The main sources of interfering signals are the inherent noise of the photomultiplier and tuned amplifier, as well as external interfering signals.

The output signal of detector *Det* proportional to the intensity of laser diode radiation at the given wavelength is applied to an automatic recorder *AR* which plots the characteristic $P_{rad}=f|\lambda|$.

The spectrograph is tuned to a certain wavelength by rotating an optical prism operated by a synchrodrive *SD*. An output pulse of light appears at the spectrograph output when it is tuned precisely to the wavelength of the laser diode radiation, the intensity of this output signal corresponding to the intensity of diode radiation at this wavelength. This signal (or rather its equivalent after amplification and detection) is measured on a paper band in the automatic recorder whose movement at a constant rate is provided by the same synchrodrive *SD* and is therefore synchronous with the rotation of the optical prism. The entire spectrum characteristic is plotted with the abscissa axis (the wavelength axis) coinciding with the direction of the paper movement and the intensity of radiation recorded in the perpendicular direction.

6.10. Automatic Measurements

Automatic measurements allow to minimize or fully eliminate human errors due to peculiarities of individuals thus improving the accuracy of type classification of semiconductor devices.

Furthermore, introduction of automatic measurements makes it possible to reduce the number of workers engaged in this work and, consequently, increase the number of production units in the workshop without infringing sanitary and technological regulations.

Such measurements may be single-position and multi-position depending on the method of measurement adopted by the manufacturer. In the first case all the parameters of a semiconductor device are measured on a single unit of production equipment; in the second case each unit of equipment is made use of to check one or several parameters.

With single-position measurements the procedure of measurement includes:

feeding the semiconductor devices to the measuring equipment;

maintaining required conditions of measurement (e.g., the specified voltage and current, temperature, humidity, etc.);

the measurements proper;

sorting of devices after measurements according to their parameters and rejection of unfit devices.

The measurements are automatic when all above operations are performed without any manual effort. In cases when even a single operation is carried out manually or only partly automated the measurements are considered to be semiautomatic.

Certain elements of automatic measurement have already been mentioned above. Thus, in some of the described circuits the test current should be maintained at one and the same value irrespective of the parameters of the devices being tested. This is implemented by the use of stabilized d.c. supply sources maintaining a preset current at any load resistance.

Measurements of laser diodes are carried out with the aid of a detector operating synchronously with the pulse source. This arrangement also includes a prism the rotation of which is synchronized with the movement of the paper chart of the recording device.

The feeder mechanism supplying the semiconductor devices being tested to the measuring unit may be a continuously or periodically moving conveyer belt equipped with a special mechanism by means of which the semiconductor devices (or containers holding several devices) are taken off the conveyer and brought up to the measuring unit. The feeder may also be in the form of a vibrating hopper consisting of a cylinder with an open upper end and a helical guide attached to its inner wall. The cylinder is loaded with a batch of devices to be tested and vibrated at mains frequency (50 hertzes) by means of specially provided electromagnets. This vibration causes the semiconductor devices to move upward along the guide, whose design provides for proper orientation of the devices. In such a way, the devices are fed to the measuring unit from the upper end of the guide.

Feeders of other types are also available, their application being determined by the specific conditions of production adopted at the given manufacturing plant.

The required conditions of measurement are maintained by means of special auxiliary units. Transformers, rectifiers, stabilizers, etc. are employed to maintain the required test voltage and current. The duration of the test is preset with the aid of special timers: delay elements, time-lag relays, etc. The sequence in which the measurements are carried out is determined by a special programming device. The specified temperature of the device case is set up and kept constant by so-called isothermal heat and cold installations. If necessary, the required humidity, frequency of vibration, and other test conditions are established by means of special equipment described in Chapter Eight.

The measurements are made with the aid of a special testing device and measuring circuit. The parameter being checked is either recorded by suitable means or converted into quantity. If necessary, the value of the measured parameter may also be checked by indicating instruments. After each test the semiconductor device is either sorted or passed on to the next unit for the measurement of other parameters; in the latter case the results of all preceding measurements are stored in some kind of memory element and the semiconductor devices are sorted after all their parameters have been measured. In either case the results of all the tests are analyzed and the measuring circuit feeds corresponding signals to the sorting mechanism.

The sorting mechanism sorts the devices according to their parameters and rejects unfit devices. Devices with parameters meeting requirements are guided into a common bin.

Figure 98 shows the block-diagram of an automatic sorting machine; this machine is used to sort *p-n* junctions according to their reverse voltages. The electric circuit of this machine employs transistor logical elements.

The measuring unit consists of a test probe and a plunger. The measurement is made by bringing the tip of the test probe into contact with the ohmic contacts of the *p-n* junction. After that the test probe is moved away from the junction, and the plunger pushes the tested crystal into a corresponding bin.

The required conditions of measurement are maintained by a source of stabilized d.c. voltage supply.

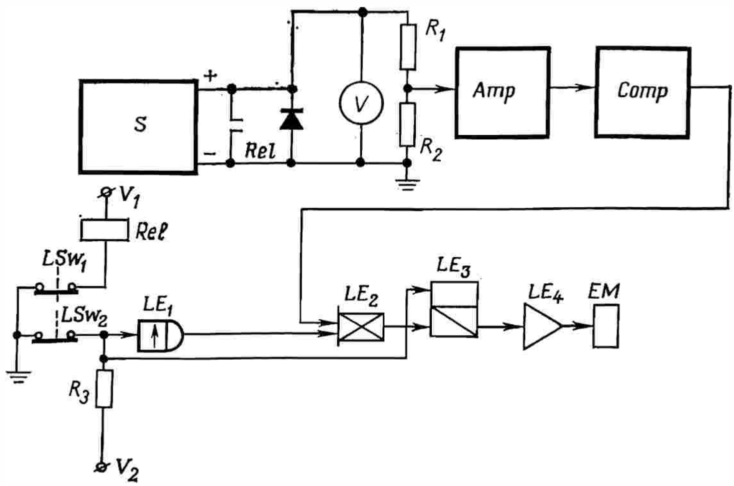


Fig. 98. Diagram of automatic machine for sorting *p-n* junctions according to their reverse voltage

S—source of stabilized voltage supply; *Amp*—amplifier; *Comp*—comparator; LSw_1 and LSw_2—limit switches; *EM*—electromagnet; LE_1-LE_4—logical delay elements

The test operations are synchronized with the movements of the test probe and the crystal under test by means of a special cam mechanism driven by an electric motor (not shown).

The test cycle begins with the crystal being placed in position for measurement. Limit switches LSw_1 and LSw_2 are normally closed and the contacts of relay *Rel* shunt the output of the source *S* of stabilized d.c. voltage supply.

Then the test probe is pressed down onto the crystal by means of a special mechanical device. As soon as the tip of the test probe comes into contact with the *p-n* junction of the crystal the first cam on the shaft of the timer opens limit switch LSw_1. This breaks the circuit of relay *Rel*, its contacts are opened and the reverse voltage is applied to the *p-n* junction under test.

At the same time a second cam on the timer shaft opens

limit switch LSw_2, thus introducing logical delay element LE_1 into the circuit. (Transistor logical networks are designed so that a binary "1" at their input corresponds to the absence of a short circuit of the input to earth.)

A voltage proportional to the reverse voltage of the *p-n* junction under test develops across resistor R_2 of voltage divider R_1-R_2; this voltage is amplified by a direct-coupled amplifier *Amp*. The function of this amplifier is to match resistor R_2 to the input resistance of comparator *Comp*. The latter generates a binary "1" if the voltage drop across the junction under test exceeds preset value. This signal is applied to the input of logical element LE_2 (an "AND"-"NO" network). After a certain time interval required for the disappearance of all transient effects (i.e., for the settlement of the output voltage of amplifier *Amp* and the comparator response time), the logical delay element LE_1 generates a binary "1" and this signal is applied to the second input of LE_2. This produces a binary zero signal at the output of LE_2 which switches the trigger ("MEMORY")—logical element LE_3 circuit. The output of LE_3, a binary "1", cuts in amplifier LE_4 and electromagnet *EM*. The latter opens the lid of the bin for fit crystals and after that the first cam returns limit switch LSw_1 to its initial normally closed position. This sets up a flow of current through the winding of relay *Rel*. As a result, the relay contacts are closed and the output voltage of supply source *S* is shunted to earth. Then the drive draws the test probe away from the crystal and the plunger pushes the tested crystal into the bin for fit devices. At this moment limit switch LSw_2 is closed. The signal delivered by limit switch LSw_2 actuates trigger LE_3 and returns it to the initial state. After that the delay element LE_1 is cut off. Then the next crystal is delivered for measurement.

In cases when the voltage drop across the *p-n* junction of the crystal under test is below specified value, the comparator does not actuate element LE_2 and electromagnet *EM* is not energized. In this case the crystal under test will be pushed into the bin for rejects. The memory element LE_3 stores the results of measurements, thus providing for proper sorting of the semiconductor devices after the test probe has been moved away from the *p-n* junction.

REVIEW QUESTIONS

6.1. Define intermediate, classification, and test measurements.
6.2. What parameters of rectifier diodes are measured?
6.3. Describe the performance of a circuit for checking the volt-ampere characteristics of semiconductor diodes.
6.4. Sketch the circuit diagrams used to measure the static and dynamic characteristics of rectifier diodes and describe their operation.
6.5. By what parameters are pulse diodes characterized?
6.6. Explain the methods used to measure $R_{p.\max}$ and τ_{off} of pulse diodes.
6.7. How is the differential resistance of reference diodes measured?
6.8. By what parameters are controlled and uncontrolled switching diodes characterized?
6.9. Sketch the circuit diagram used to measure V_{sw} and I_{sw} of switching diodes and explain its operation.
6.10. Explain the method of measuring I_{cutoff}.
6.11. What are the main transistor parameters?
6.12. Sketch the circuit diagram used for measurement of reverse collector current.
6.13. Explain the method of measurements of the modulus of the current-amplification factor.
6.14. How is the maximum oscillation frequency measured?
6.15. How is the alpha-cutoff frequency measured?
6.16. What is the method for forward transfer admittance measurement?
6.17. Explain the method used to measure the time constant of the internal feedback of a transistor.
6.18. What parameters are used to characterize tunnel diodes and how can they be measured?
6.19. Sketch the circuit diagrams used to measure the parameters of photodiodes, phototransistors, and photoresistors and explain their operation.
6.20. In what way can the output power of laser diodes be evaluated?
6.21. Explain the principle of operation of the installation used to measure the radiation spectrum of laser diodes.
6.22. What are the advantages of automatic measurements of semiconductor devices?

CHAPTER SEVEN

Adjustment of Semiconductor Devices

For operation on high and super-high frequencies semiconductor devices should possess very low parasitic (internal) capacitance and inductance. The internal inductance of a diode is mainly determined by its design, while its internal capacitance depends, on the whole, on the surface of the rectifying structure. Diodes with the minimum values of internal capacitance (with the least geometric dimensions of the rectifying structure) are made by bringing a tungsten point in contact with the crystal of the semiconductor material. Obtaining a rectifying structure possessing given electrical parameters is connected with appropriate selection of the pressure of the point on the crystal and the place where they come in contact.

When such devices are made individually, the place of contact of the point with the crystal and the pressure of the point on the crystal should be selected for each device. The technological operation performed for obtaining a rectifying structure possessing given electrical parameters is called *adjustment* of a semiconductor device. Devices are adjusted with the aid of special equipment. The design of the equipment, as well as the adjustment technology depend on the purpose and type of the device. The adjustment of semiconductor devices is a complex and time-consuming technological operation. At the present time the trend is to employ such a technology in manufacturing devices that would do away with the need of adjustment.

Adjustment is done during the process of assembling the device. The adjustment process is monitored by measuring the electrical parameters of the obtained rectifying structures. Therefore, in this book adjustment is dealt with after describing methods of measurement.

7.1. Adjustment of Pulse Diodes

At present a number of pulse diodes are manufactured by the mesa-technological method. A mesa-structure possesses a low capacitance and, correspondingly, a higher frequency limit, and also offers better removal of heat from the *p-n* junction.

Mesa-diodes are adjusted with the aid of the device shown in Fig. 99. The half-finished diode (envelope with

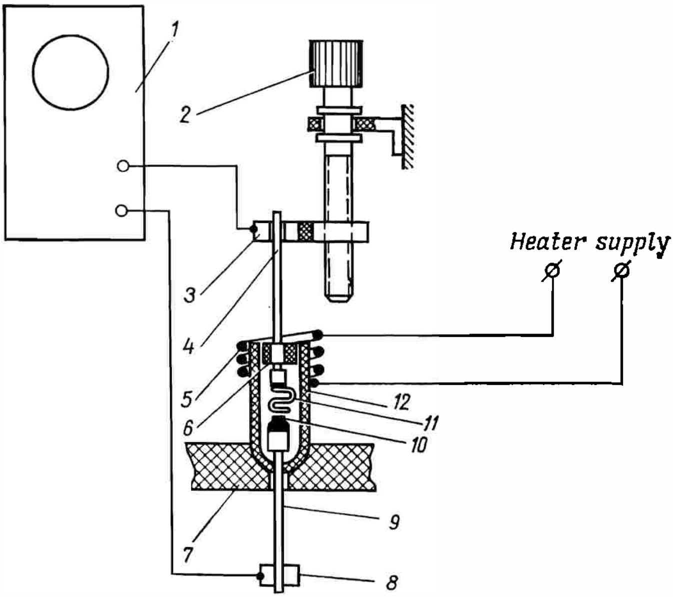


Fig. 99. Arrangement for adjusting mesa-diodes

1—response meter; *2*—adjusting screw; *3*—upper collet; *4* and *9*—diode terminal leads; *5*—heater; *6*—glass bead; *7*—holder; *8*—lower collet; *10*—crystal; *11*—contact point; *12*—diode envelope

beaded-in leads and a crystal) is fitted into the socket of holder *7*. Upper lead *4* with glass bead *6* is secured in collet *3* with the aid of adjusting screw *2* and lowered into envelope *12* until point *11* comes into contact with crystal *10*. The moment of contact is registered by the diode

characteristic curve on the screen of response meter *1**. After this heater *5* is energized. The current flowing through the heater heats up the upper part of the envelope and the bead and fuses them. On being fused, the position of the contact point and the crystal are fixed.

After adjustment, the diode is subjected to ageing, a second measurement of parameters, painting, packing and is delivered to the consumer.

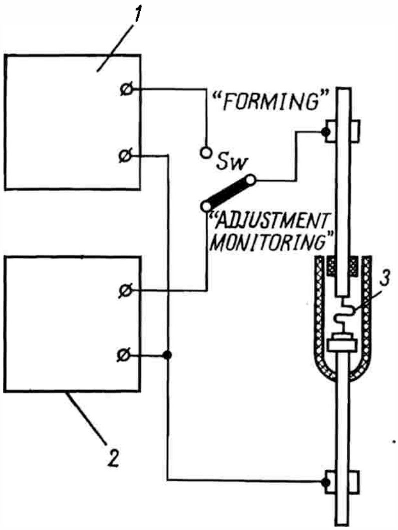


Fig. 100. Arrangement for adjusting high-frequency diodes
1—electric-forming unit; *2*—monitoring unit; *3*—contact point

7.2. Adjustment of High-Frequency Diodes

In some high-frequency diodes the rectifying structure is produced by an electric-forming (point-contact) method. Such high-frequency point diodes are adjusted with the aid of the device shown in Fig. 100.

The design of the assembly for moving the diode lead together with the contact point is similar to that shown in Fig. 99. The diode is adjusted in the following way. As in the adjustment of mesa-diodes, the envelope with the lower lead and the crystal of semiconductor material is fitted into the holder. The upper lead with the glass bead and contact point *3* are fitted into the collet of the travel mechanism. Switch *Sw* is set in the ADJUSTMENT MONITORING position. The lead with the point is brought to

* A response meter is an instrument combining an oscilloscope with a special measuring attachment, the circuit of which was described in Paragraph 5.11.

the crystal by means of the adjusting screw. The moment of contact is registered by the pointer instrument of monitoring unit *2*. The instrument indicates the reverse current of the temporary *p-n* junction formed by the point contacting the crystal.

By varying (with the aid of the adjusting screw) the pressure of the point of the lead on the crystal, the operator obtains a reverse current of the *p-n* junction formed by the contact between the point and the semiconductor crystal, that does not exceed a given value. If the reverse current does not exceed the given value, the operator manipulates switch *Sw* to the "FORMING" position and depresses the starting push button of electric-forming unit *1*. The electric forming unit produces a single, unipolar pulse. The amplitude of the pulse and its duration are selected depending on the type of diode (the current is set to be from 1.5 to 2.7 amperes at a duration of 15 to 30 microseconds). After the end of the electric-forming pulse, the switch is set in the "ADJUSTMENT MONITORING" position, the diode is allowed to cool until its reverse current has stabilized, and then the forward voltage drop is checked at the value of forward current given in the specifications. Then the reverse current is measured at the given reverse voltage. Measurements are made under dynamic conditions.

If the forward voltage drop V_{for} exceeds the normal, forming is repeated with a current 1.5 to 1.8 times greater than in the first forming.

If the value of the forward voltage drop and the reverse current of the diode after forming are within the given limits, the envelope and the bead are fused. On being fused the position of the contact point with respect to the crystal is fixed.

7.3. Adjustment of Tunnel Diodes

To make a diode possessing a given value of maximum current I_{max}, after the crystal has been fixed in assembly, it is etched a little in hydrofluoric acid. For this a special support is used (Fig. 101). The support has two contact terminals *3* which are connected to an instrument for observing volt-ampere characteristics by means of wires *4*. The operator dips diode *1* into the hydrofluoric acid and

keeps it there for five to six seconds. Then the volt-ampere characteristic curve of the diode is observed on the oscilloscope screen.

After etching and prior to the characteristic curve, the

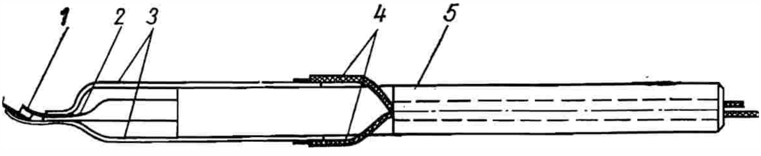


Fig. 101. Support for etching tunnel diodes
1—tunnel diode; 2—insulation insert; 3—contact terminals; 4—connecting wires; 5—handle

diode should be washed so that remnants of the hydrofluoric acid do not distort the volt-ampere characteristic.

Check lines are applied to the oscilloscope screen. The operator etches the junction until the value of I_{max} coincides with check lines *CL*. Figure 102 shows the characteristic of a diode with an under-etched junction (Fig. 102*a*) and of a diode with I_{max} of specified value (Fig. 102*b*).

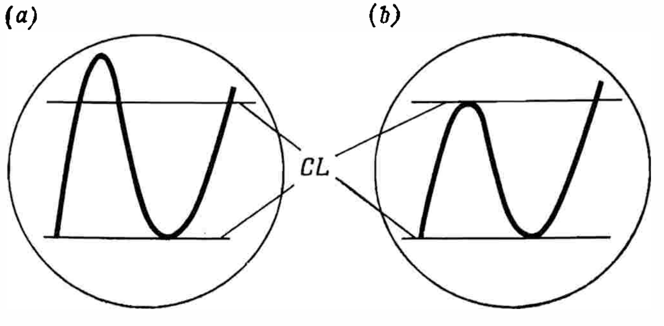


Fig. 102. Volt-ampere characteristics of tunnel diodes
(*a*) diode with under-etched junction; (*b*) diode with I_{max} equal to specified value

When manufacturing tunnel diodes with various values of I_{max} the position of the check lines remains constant, instead the voltage applied to the oscilloscope input is varied with the aid of a voltage divider.

7.4. Adjustment of Microwave Diodes

In SHF circuits it is not easy to obtain super-high frequency oscillations stable in frequency. Sometimes SHF oscillations are obtained by employing the frequency multiplication method. For this purpose use is made of microwave multiplication diodes.

With the aid of microwave diodes, sinusoidal oscillations are converted into non-sinusoidal oscillations. Distortion of the sine-wave shape is obtained by shifting the operating point of the volt-ampere characteristic of the diode to the curvilinear section. The non-sinusoidal oscillations thus obtained may be regarded as a row of sinusoidal harmonic components (harmonics). The frequencies of these oscillations are multiples of the fundamental oscillation frequency, i.e.,

$$f_1 : f_2 : f_3 : f_n = 1 : 2 : 3 : n,$$

what is more

$$f_1 < f_2 < f_3 < \ldots\ldots < f_n$$

Figure 103 shows a hookup for adjusting microwave multiplication diodes on one of the harmonics (from the 1st to the 8th) of the fundamental frequency produced by the SHF generator.

The hookup is essentially a system of rectangular waveguides, which forms a line for transmitting SHF oscillations.

By *waveguide* is conventionally meant a metal tube of round or rectangular cross section, which possesses a good conducting inner surface and a definite relationship between the dimensions of the cross section and the wavelength. Waveguides are connected with one another and with other components of an SHF circuit with the aid of flange joints *FJ*.

The diode is placed in the multiplication chamber and adjusted to maximum power on one of the eight harmonics singled out of the harmonic spectrum. The oscillations are fed into the waveguide system from the SHF generator via coaxial connecting cable *CC*. The central conductor of the coaxial cable is connected to the central probe. The

probe of the coaxial cable introduced into the coaxial coupler CC_0 radiates SHF oscillations into the waveguide channel. The continuous SHF oscillations are supplied via a ferrite unidirectional filter (serving for decoupling the elements of the coaxial channel and the multiplication chamber) to the input of the multiplication chamber MC. The diode (AD) to be adjusted is inserted into the socket of the multiplication chamber.

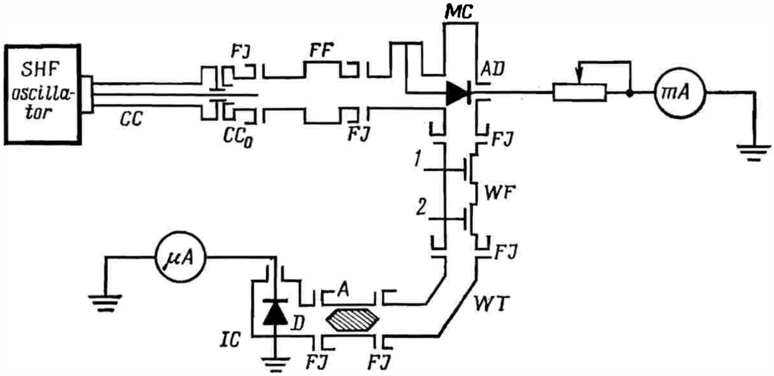


Fig. 103. Hookup for adjusting microwave diodes

CC—coaxial connecting cable; CC_0—coaxial coupler; FF—ferrite filter; MC—multiplication chamber; AD—diode to be adjusted; WF—wave filter; WT—waveguide turn; A—attenuator; D—detecting diode; IC—indication chamber; FJ—flange joints

In the multiplication chamber the SHF oscillations of the fundamental frequency are converted into a large number of harmonic components of the oscillation with the aid of the diode being adjusted.

The location of the operating point on the volt-ampere characteristic of the microwave diode is selected with the aim of obtaining the maximum amplitude of the harmonic components at the output of the multiplication chamber.

For singling out a given harmonic a wave filter WF is connected at the output of the multiplication chamber; it can be tuned to the given frequency with the aid of tuning elements *1* and *2*.

The oscillations singled out are supplied into indication chamber IC, having first passed through attenuator A which is used for reducing the interaction between the multiplication and indication chambers. In the indication chamber the oscillations are detected (rectified) by diode D. The

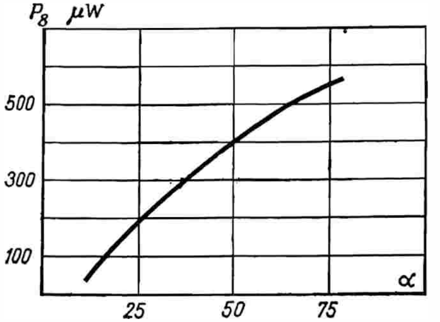


Fig. 104. Calibration curve for oscillations of the eighth harmonic

current of diode D is proportional to the power of the harmonic to which the diode is tuned, as supplied to the input of the indication chamber. The rectified current of the detecting diode is read from the scale of microammeter μA. The power of the singled-out harmonic is determined with the aid of the calibration curve supplied with the certificate of the device. The calibration curve shows how the power of harmonic P_n depends on the current α, where α is the deflection of the microammeter pointer proportional to the rectified current of the detecting diode.

Figure 104 shows a calibration curve for oscillations of the eighth harmonic.

The diode is adjusted to one of the harmonics in the following way. Diode AD is inserted into the socket of the multiplication chamber. In conformity with the specifications of the device, the diode bias voltage is set with the aid of the rheostat. By turning adjusting element *3* of the diode (Fig. 105) with a special screw-driver, the pressure of point *6* on crystal *5* is adjusted, as well as the place of the contact, so as to obtain the power on the given harmonic, conforming to the specifications of the device. The power of the singled-out harmonic is read from the meter μA (see Fig. 103).

After adjusting the device; its operation is checked in the course of two to five minutes, keeping an eye on variations of the power of the n-th harmonic with time. The variations in the power of the harmonic should lie within

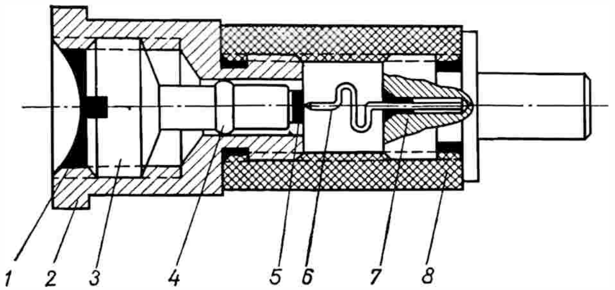


Fig. 105. Typical construction of point microwave diode

1—epoxy resin; 2—flange (silver-plated brass); 3—adjusting element; 4—shunting band; 5—silicon crystal; 6—tungsten contact point; 7—contact holder (silver-plated brass); 8—ceramic tube

the permissible limits stated in the specifications of the device.

If a device has passed the test for operating capacity, the position of the adjusting element is fixed by sealing it with epoxy resin. The epoxy seal makes the device hermetical.

REVIEW QUESTIONS

7.1. Which technological operation is known as adjustment of semiconductor devices?
7.2. How are pulse mesa-diodes adjusted?
7.3. What is the essence of electric forming?
7.4. Which operation completes the adjustment of high-frequency diodes?
7.5. How is the adjustment of tunnel diodes monitored?
7.6. Explain the design of the device and the procedure for adjusting microwave diodes.

CHAPTER EIGHT

Testing Semiconductor Devices

8.1. Effect of Ambient Medium on Semiconductor Devices

Semiconductor devices are used in a great variety of electric and electronic equipment operating under various conditions. Some apparatuses used at sub-zero Centigrade temperatures, others are used in a tropical climate, while measuring equipment must operate reliably both at low and high temperatures. Sometimes semiconductor devices must provide failure-proof operation of the equipment at rapid temperature changes within a wide range.

Semiconductor devices used in aviation, machine-tool manufacture, transport, and certain other fields of applica-

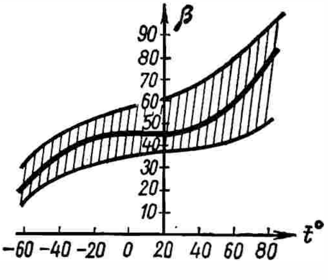


Fig. 106. Typical current gain *vs* temperature curve

tion must be capable of resisting high values of accelerations and vibration encountered in service.

Semiconductor devices must resist the effects of occasional mechanical impacts. It should be noted that the parameters of semiconductor devices depend to a large extent on the operating conditions, most of all, on the ambient temperature. This is a characteristic feature of semiconductors determined by their physical properties (see Chapter Three).

Figure 106 illustrates typical curves characterizing the dependence of the current gain β on temperature. It is clear that the gain only slightly changes within a temperature range from minus 10° to plus 40°C. At a temperature below minus 10°C the gain decreases considerably while at temperatures above plus 40°C the gain sharply increases.

Other parameters of semiconductors and, therefore, their characteristics also depend greatly on temperature.

In the process of storage and operation of semiconductor devices their parameters may change (drift). The most important are the drift of reverse currents of the junctions and of the amplification factor of transistors.

The reverse currents of the junctions may increase or decrease considerably depending on the type of a semiconductor device and the method of its manufacture, while the change in transistor amplification factor is usually not higher than 50 per cent.

The parameters of semiconductor devices also depend on the quality of their manufacture. If the seal of the case of a semiconductor device is broken during manufacture or due to mechanical loads in the process of operation, moisture and dirt will penetrate into the device and cause a considerable drift of its parameters. During manufacture some elements of a semiconductor device may be loosely secured on their supports, the ohmic contacts may be of poor quality, the *p-n* junction itself may be defective, etc.

In order to check the parameters of a semiconductor device under various operating conditions and to check the quality of manufacture they are subjected to a variety of tests.

8.2. Classification of Tests

The tests of semiconductor devices are effected in accordance with technical requirements which are subdivided into construction, electrical, mechanical, and climatic.

The technical requirements that are to be met by semiconductor devices are usually given in specifications. Specifications are classified as general specifications for all semiconductor devices and type specifications for devices of the same model.

General specifications envisage the following groups of tests: (1) acceptance tests; (2) periodic tests; (3) construction tests; (4) life-span tests; (5) sample check tests.

Acceptance tests are used for checking each batch of devices submitted for acceptance. These tests are effected by the inspection department of a manufacturer. The conformity of the submitted batch with general and type specifications is checked at random according to the order determined by the general specifications. Should acceptance tests yield unsatisfactory results, the batch submitted for testing is returned to the manufacturer as a product not complying with the general and type specifications.

Periodic tests are carried out by the manufacturer's inspection department regularly once a month and also, in the case of changes in the design of semiconductor devices and the manufacturing process, use of different materials or any other changes liable to affect the quality and parameters of the devices. The scope and sequence of these tests are stipulated in general specifications.

Construction tests are carried out when a device is manufactured for the first time. These tests are usually combined with official state tests when approving the device for serial production. They are also performed when changes in the design or materials are made if this may affect the quality and parameters of the devices.

The tests are effected in compliance with the program given in the general specifications.

Life-span tests are effected by the inspection department. The semiconductor devices are selected for these tests in quantities determined by the general and type specifications, and the specimens are taken from the month's production. Subjected to these tests are the devices which have preliminarily passed periodic tests. The results of the life-span tests are estimated monthly by the total quantity of the tested semiconductor devices.

Sample check tests are effected by a research-and-development organization in the presence of the manufacturer's representative according to a special schedule.

The devices for these tests are selected in quantities specified by the general specifications from the total amount of semiconductor devices accepted in the current month.

The scope of the tests is stipulated in the general and type specifications.

The results of all tests, except for the sample check tests, are entered in a special certificate. The sample check tests are recorded in a special test report which is sent to the manufacturer.

General specifications describe the methods of conducting the tests of semiconductor devices, namely, they give a detailed description of the test procedure used to determine whether the parameters of the devices comply with the electrical, mechanical, climatic, and construction requirements.

In addition, the general specifications include the following items: the requirements to the marking and packing of the devices; the requirements to the testing apparatus, equipment, and electric instruments; the manufacturer's guarantees; operating instructions and recommendations for the user.

Type specifications are provided for each series of semiconductor devices on the basis of the general specifications. The type specifications include the following information: the method of mounting the devices, the number of devices to be tested simultaneously, the dimensions of heat radiators, the method of heat dissipation, the stress as well as the method and direction of its application during mechanical tests, duration of tests, allowable spread of parameters tested, the current and voltage waveforms.

In addition, type specifications determine the categories of tests for devices of a given model and the types of tests in each category as well as the conditions under which the tests are to be carried out.

The standards for the parameters being measured are divided into shop standards and inspection department standards. According to shop standards the values of the measured parameters must be 20-50 per cent higher than the values guaranteed by the manufacturer and specified in the certificates, reference books, and catalogues.

The inspection department tests the marked device according to the classification model ascribed.

In accordance with the requirements to be met by semiconductor devices, four categories of tests are carried out, namely, electrical, mechanical, climatic, and construction.

8.3. Construction Tests

The check for compliance of the construction of the device with standard requirements includes tests for checking the dimensions, mechanical rigidity of the leads, the quality of the corrosion-resistant coating, the quality of case seals, opacity, quality of tinning and welding, the quality of the glass as well as the weight of the device.

The overall and mounting dimensions of semiconductor devices are checked by means of general-purpose measuring instruments and special gauges.

The mechanical rigidity of flexible leads and their attachment are checked by repeatedly bending and pulling them. Each lead must withstand at least five bendings of a radius of 1.5 to 3 mm at an angle of 90° and a distance at least 3 mm from the glass. During the test each lead is pulled with a force of 460 ± 20 gf.

The quality of the corrosion-resistant coating is checked by visual inspection.

The quality of the case seals is checked by the following methods: method of radioactive analysis, helium method, and method of testing with heated oil.

The method of radioactive analysis is the most complex and expensive. It consists in that the semiconductor devices to be tested are placed in a pressurized chamber which is then filled with a radioactive gas. After removal of the gas the devices are withdrawn from the chamber and checked for radioactive radiation. If the tested device is not leak-proof, the radioactive gas penetrates into its case and on withdrawal from the chamber such a device becomes a source of radioactive emission. The above-described method makes it possible to determine the magnitude of the leak within rather a wide range.

The helium method consists in filling the devices with helium and then detecting any flow of gas through leaky joints by means of a leak tester. This method is more simple than that described above.

The method of testing with heated oil is the most simple and inexpensive of all, because it does not require sophisticated equipment and preparations. The finished semiconductor devices are immersed in a vessel with a transparent

oil heated to a temperature of about 120°C. Due to the action of temperature the pressure of the air inside the cases of the devices increases and air bubbles appear at leaky joints.

In addition, the quality of case seals is checked during the tests for moisture resistance (short-term action) according to the method described in Sec. 8.6.

The opacity is checked by changes in the reverse current of the devices under the conditions stipulated in the type specifications. The reverse current is first measured in a shaded device and then during its illumination by means of a 100-watt filament lamp placed at a distance of 200 to 300 mm from the device. During this test a flat transparent vessel filled with water is placed between the light source and the device to prevent excessive heating of the latter.

The quality of tinning of the leads is checked during the acceptance tests by visual inspection, whereas during the periodic tests it is checked by the wettability of the leads with solder.

For checking the wettability the tinned portion of the leads is immersed into a bath with a molten tin-lead solder for two or three seconds. After withdrawing the leads from the bath, the quality of tinning and their appearance are checked visually, and the most important parameters of the devices specified in the acceptance tests are measured.

The quality of welded joints is checked by visual inspection. The heat-resistance of the glass and the glass-metal alloy is determined in the course of the cyclic temperature tests described in Sec. 8.6.

The quality of the glass and ceramic components is also to be checked by inspection with the aid of a magnifying glass, microscope, and other means.

The requirements to construction also call for the complete absence of any moving particles within the semiconductor device. This is checked during the vibration test by the method described in Sec. 8.5.

8.4. Electrical Tests

Semiconductor devices are to meet the following electrical requirements:

(1) The electrical parameters and characteristics of the

devices shall be as stipulated in the specifications for the given type of devices during their operation and after transportation and long-term storage.

(2) The electrode circuits shall be free of short circuits or breaks, whether temporary or permanent.

(3) The devices shall ensure reliable operation throughout the time stipulated in the general and type specifications.

The electrical parameters and characteristics of the devices are measured and checked by the methods described in Chapter Six. The sequence, operating conditions, and accuracy of the measurements are stipulated in the type specifications.

The electrical parameters are checked almost after each kind of mechanical and climatic tests. Furthermore, purely electrical tests are effected for checking the operational capability of the devices and the stability of their parameters under operating conditions.

The operational capability of semiconductor devices is checked by means of a so-called ageing test. Two methods of ageing are known: electric and thermoelectric. For the electric ageing test the devices are connected to a circuit in which rated values of forward current and reverse voltage are maintained throughout the test. The devices are kept under these conditions for several hours (according to the type specifications). During the operation of the circuit special arrangements record the failure of any of the semiconductor devices being tested. After the ageing test the main electrical parameters of the tested device are measured.

During the thermoelectric ageing the test semiconductor device is placed into a chamber in which a high temperature, the maximum allowable for the given type of the devices, is maintained. Thus, the maximum current load is simulated. During the tests the temperature within the chamber is automatically maintained constant. The device is inserted into the electric circuit and the maximum reverse voltage is applied to the device. The device is kept under these conditions for several hours (depending on the type of the device being tested). After the ageing test the electrical parameters of the device are measured. Sometimes the parameters are measured during the ageing test (periodically

or continuously). The continuous measurements may be effected with the aid of an automatic recording instrument.

The methods of ageing of various semiconductor devices are basically the same as concerns the way in which the device is connected to the electric circuit and the method used for measuring its parameters. Therefore, it is sufficient to consider a circuit for ageing one kind of semiconductor devices. As an example, let us consider the circuit of a test stand for thermoelectric ageing medium-power semiconductor diodes (Fig. 107). The circuit includes a

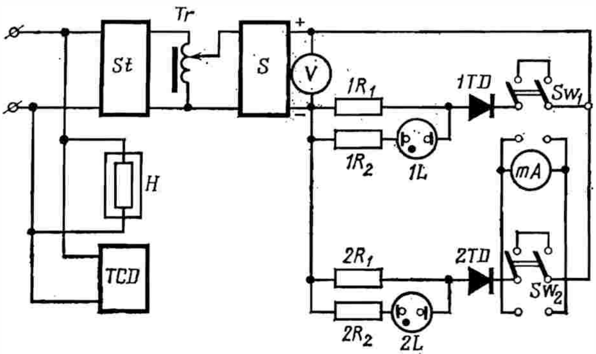


Fig. 107. Test circuit for ageing diodes

H—heater; *TCD*—temperature control device; *1L* and *2L*—neon lamps; *1TD* and *2TD*—diodes being tested; Sw_1 and Sw_2—selector switches; *St*—voltage stabilizer

heater *H* with a temperature control device *TCD* and a circuit for connecting and testing semiconductor diodes *1TD* and *2TD*. The diodes operate under static conditions and are connected in the non-conducting direction. The diodes are fed from a source of d.c. supply *S* the input of which is connected to the mains via a voltage stabilizer *St*. The magnitude of the d.c. voltage can be varied by autotransformer *Tr*. The maximum reverse voltage for this particular device type is applied to the diodes. Resistors $1R_1$ and $2R_1$ limit the current in the circuit in the case of breakdown of the diodes being tested (short circuit of the electrodes). The breakdown is indicated by a neon lamp

1L (2L). Under normal conditions the lamp does not glow since a very low voltage is applied to it. The greater portion of the applied voltage drops on the back resistance of the diode *1TD (2TD)* being tested.

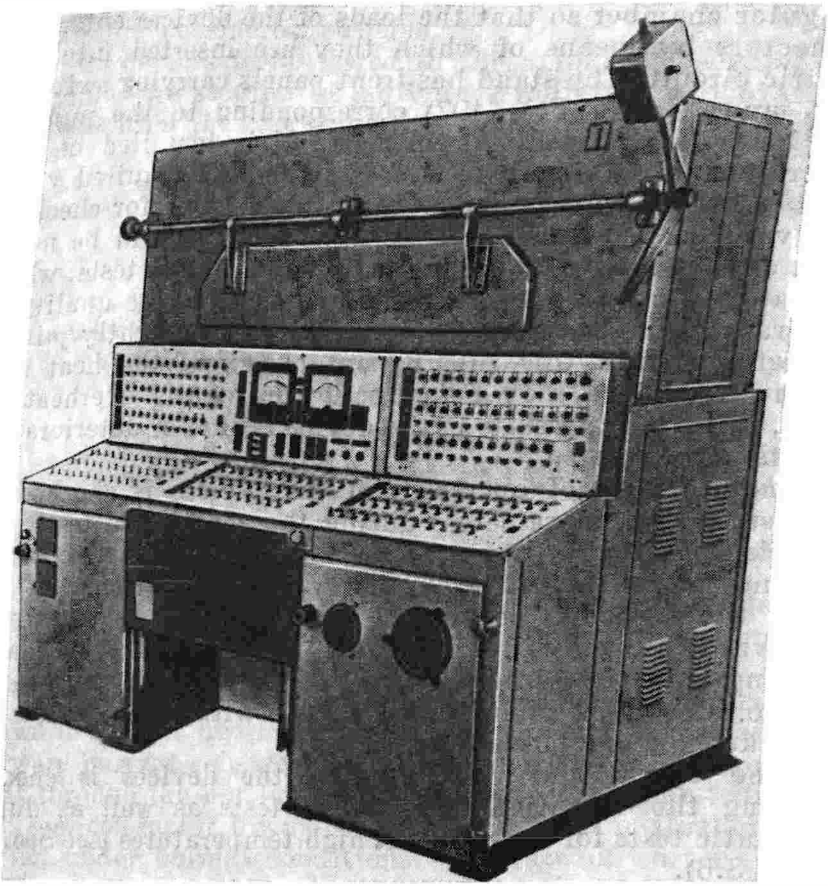


Fig. 108. General view of test stand for ageing diodes

The circuit makes it possible to periodically measure the reverse current of any of the diodes during the ageing test. For this purpose the switch Sw_1 (Sw_2) is shifted to the lower (as shown in the diagram) position. A milliammeter *mA* is connected in series with the diode.

Practically the test stand is used for testing dozens or hundreds of semiconductor devices simultaneously.

Figure 108 presents the general view of a test stand for temperature ageing semiconductor diodes. The diodes to be tested are mounted on radiators and placed into a large rectangular chamber so that the leads of the devices enter the connectors by means of which they are inserted into the electric circuit. The stand has front panels carrying switches (Sw_1 and Sw_2 in Fig. 107) corresponding to the number of diodes being aged. A voltmeter V is installed on the central panel, which is used for setting the required value of the reverse voltage and a milliammeter mA for checking the value of the diode reverse current. It should be noted that during this test, as well as during climatic tests, where radiators are used, it is necessary to control the quality of the radiator surface and that the devices be tightly jointed thereto. Should this rule be not observed, the heat sink from the device may be reduced causing its overheating; this, in its turn, results in the device failure or deterioration of its parameters.

The stability of operation of the devices is checked by measuring the parameters during the acceptance tests. For checking the stability each parameter is measured during a time period specified in the type specifications. In this case the device is considered as having passed the test if the value of each of the measured parameters did not change during this time interval or changed within a permissible range. The short circuits and breaks within the devices are checked during mechanical tests.

The operational reliability of the devices is checked during the vibration and impact tests as well as during climatic tests for operation at high temperatures (see Sec. 8.5 and 8.6).

Still another method of checking the reliability of the devices consists in checking their long-term operation at normal temperature (life-span test). In addition, some devices are subjected to forward current overload tests. These kinds of tests are used for checking individual devices or groups of devices selected from each batch at random. Depending on the results of these tests, the entire batch is either accepted for operation or rejected.

The life-span tests are carried out with the device under maximum permissible temperature and electric duty conditions specified for given type of the device.

If at the end of the tests the number of faulty devices is less than a predetermined per cent, the results of the tests are considered positive.

The devices to be tested in the amount of several dozen samples are secured to individual radiators which are then mounted on the test stand at normal temperature. Each de-

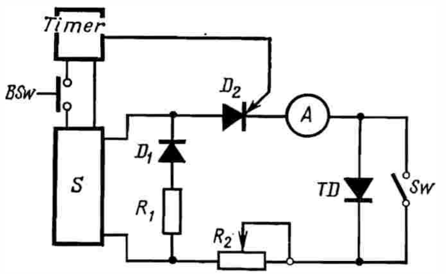


Fig. 109. Circuit for forward overcurrent

vice is inserted into the electric circuit for the entire period of the tests. The test is effected during 400 or 500 hours according to specifications. The tests are made under the dynamic conditions of operation. The devices are connected to a conventional circuit.

Each semiconductor device must withstand a short-term forward current overload. This means that when passing a forward current considerably in excess of the maximum current through the *p-n* junction, during a short time interval, the semiconductor device must remain fit for further operation under normal conditions. The rate of current overload and its duration are specified in the type specifications.

Figure 109 shows a circuit for testing the diodes for forward current overload. A similar circuit is used to test collector and emitter junctions of transistors. An a.c. pulse of a given magnitude from a source *S* is fed through the diode *TD* being tested. The pulse duration is preset by a timer. When depressing the push-button switch *BSw*, the signal from the output of the timer renders the controlled diode

D_2 conductive, and the overload current flows through diode D_2 to the diode being tested. The controlled diode is cut off by the timer when the value of the testing current (half-wave) is equal to zero.

The value of the testing current is set by the ammeter A with the help of a rheostat R_2 at the closed position of the switch Sw.

After conducting the tests for checking the reliability of the devices, their electrical parameters are measured. The devices are considered as having passed the test if in the process of testing and after the tests they prove to be free of defects affecting their normal operation, have an appearance complying with respective specifications, and their electrical parameters (or variations of these parameters) remain within the limits stipulated in the type specifications for the given test.

8.5. Mechanical Tests

In mechanical tests semiconductor devices are checked for:

resistance to long-term vibration within a specified frequency range;

vibration strength within a specified frequency range;

resistance to long-term vibration on a fixed frequency;

resistance to multiple impacts;

resistance to a single impact;

resistance to continuous acceleration.

Mechanical tests are conducted at regular intervals on a small group of devices selected from each batch of current production. The results of the tests are the basis for the acceptance of the devices of the whole batch.

The tests are effected with the devices rigidly secured on the platforms of test stands in order that the action of the load is transferred to the devices with minimum losses (without shock absorption). The force is applied to the devices in two most dangerous positions specified in the type specifications.

The devices are tested under specified conditions (except for the tests for long-term vibration within a frequency range). The devices are visually inspected after each kind

of test, and the electrical parameters are measured by the methods described in Chapter Six. Conditions for measuring the electrical parameters are listed in the type specifications.

The resistance of the devices to long-term vibration within a specified frequency range is checked on a vibration stand providing harmonic vibration without applying any voltage to the electrodes. The test is carried out within a frequency range from a few hertzes to several kilohertzes with a prescribed acceleration. The frequency range is subdivided into fourteen bands. During the test the frequency is continuously varied within each band. The time of passing the band is of the order of a minute. On the highest frequency of each band the devices are held during the time stipulated in the general specifications (a few hours).

The devices to be tested on a vibration test stand are installed in a given position on a common adaptor (magazine) in the amount of a few dozens of samples in each adaptor. Several adaptors (depending on the dimensions of the devices) are placed on a special horizontal platform of the vibration stand, which vibrates at a specified frequency in a vertical plane.

Two types of vibration test stands are employed, namely, electromechanical and electrodynamic. The platform of electromechanical stands is vibrated due to the rotation of unbalanced discs actuated by an electric motor. These stands cannot provide a wide range of frequencies and accelerations. The platform of electrodynamic stands is vibrated as a result of the interaction between the magnetic fields of a stationary permanent magnet and a moving coil whose winding is fed with an alternating current of a desired frequency and voltage. These vibration stands provide vibration over a wide range of frequencies and accelerations.

The vibration strength within a specified frequency range is checked with the devices operating under specified conditions. The devices placed in the adaptors and mounted on the vibration stand are connected with an indicating circuit by means of special connectors and are kept in this position during testing. On the signal panel each device being tested corresponds to a group of signals indicating the presence of short circuits or breaks of the corresponding *p-n*

junctions within the device. A memory device stores signals corresponding to even short-term breaks or short circuits to the end of the tests. The tests are performed on several frequencies in various bands. If frequencies causing semiconductor device failures are detected, the entire batch of the devices is additionally tested for vibration on these frequencies.

The resistance of the devices to long-term vibration on a fixed frequency is checked on a vibration test stand providing sinusoidal vibration. The test is carried out on a prescribed frequency with a given acceleration during a few dozens of hours in each position of the device.

The resistance of the devices to multiple impacts is checked on an impact test stand. In each position the device is subjected to a specified number of impacts with a very high acceleration.

For testing on an impact test stand the devices are fixed on adaptors mounted on a massive horizontal steel plate which is free to move along vertical guides. The plate is lifted to the upper position by the action of a cam mounted on a shaft rotated by a d.c. motor. The cam is of such a shape that when the plate is lifted to the upper (dead) point, it abruptly drops down under the action of a strong spring. While dropping the plate strikes the supports.

The height of lifting the plate can be adjusted by changing the height of the cam. The impact frequency can be adjusted by changing the number of revolutions of the d.c. driving motor.

The resistance of the devices to a single impact is tested on an impact stand with an acceleration which is much higher than the free-fall acceleration and at very short duration of the impact.

During the tests the devices are placed into a metal case filled with paraffin or other material having a melting point lower than the maximum operating temperature of the device. The devices are subjected to ten impacts. The tests may be effected by throwing the case with the devices on an iron plate.

Before checking the electrical parameters, the devices are removed from the case by melting the paraffin, washed, and dried.

The resistance of the devices to continuous acceleration is checked on a centrifuge.

The test is conducted at an acceleration of 150 grams during a few minutes in each position of the device. The acceleration must be applied approximately to the geometric centre of the device.

The devices are considered as having passed the test if in the process of testing there were no breaks of contacts or short circuits, and if after the tests they prove to be free of defects affecting their normal operation, have an appearance complying with respective general and type specifications, and their electrical parameters (or variations of these parameters) remain within the limits stipulated in the type specifications for the given test.

8.6. Climatic Tests

In climatic tests semiconductor devices are checked for:

heat resistance;

cold resistance;

moisture resistance (short-term and long-term tests);

resistance to thermal cycling;

resistance to reduced atmospheric pressure;

resistance to elevated atmospheric pressure;

resistance to the action of sea fog.

All manufactured semiconductor devices are subjected to the shop climatic tests. Some types of devices are not subjected to the climatic tests at all.

The heat resistance of the devices is checked in a heat chamber at a temperature of 70 °C (for germanium devices) or 120 °C (for silicon devices).

The heat chamber consists of a pressurized volume with good thermal insulation of the walls equipped with heaters. The chamber is provided with a fan to provide uniform temperature distribution within the inner volume of the chamber by forced agitation of the air.

The temperature in the chamber is maintained automatically by means of a temperature control device.

The semiconductor devices arranged in adaptors are placed into the chamber so that each device is connected to a measuring circuit. The devices are held in the chamber under

rated electrical conditions corresponding to this temperature during a time sufficient for a thorough heating of the devices. The time of exposure and the electrical operating conditions during the tests are stipulated in the type specifications. The electrical parameters of the devices stipulated in the type specifications for the given kind of the tests are then measured directly in the chamber.

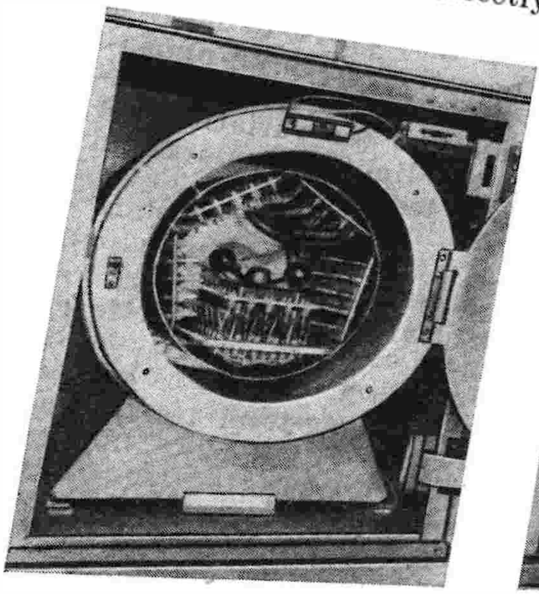


Fig. 110. Heat chamber

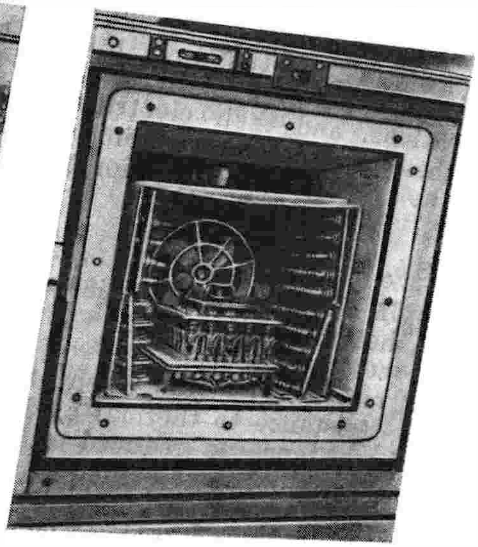


Fig. 111. Cold chamber

After the tests the devices are withdrawn from the chamber and are kept under normal climatic conditions for 24 hours. Then the electrical parameters are measured in accordance with the measurement procedure of the acceptance tests.

Figure 110 illustrates a heat chamber (with an open door) intended for testing semiconductor diodes, type D242-D246, D231-D234. The diodes to be tested are fixed in an adaptor placed in the lower part of the chamber so that the lower leads of the diodes tightly enter special plug and socket units connected to a measuring circuit.

Mounted on the walls of the chamber are adaptors which

are not inserted into the electric circuit. Here the diodes are preheated to a prescribed testing temperature.

The cold resistance of the devices is checked in a cold chamber at a temperature of minus 60°C. In principle the cold chamber does not differ from the heat chamber. The main difference consists in that instead of the heaters the cold chamber is provided with an evaporator in which liquid nitrogen which is fed from a Dewar vacuum flask is evaporated. In the Dewar flask the nitrogen is in a liquid state under a high pressure. The nitrogen fed into the evaporator increases in volume, i.e., it turns into the gaseous state (evaporates). In this case a large amount of heat is absorbed from the evaporator surface. The evaporator surface, in its turn, absorbs the heat from the volume of the cold chamber causing a decrease in temperature within the chamber.

The chamber is equipped with a fan. The predetermined temperature is maintained automatically. The tests are carried out in the same manner as in the heat chamber.

Figure 111 shows a general view of a cold chamber for testing diodes (the door is open). The diodes to be tested are arranged in the same fashion as in the heat chamber. Figure 112 illustrates a test stand for testing the semiconductor devices for thermal resistance. Located at the right-hand side of the stand are heat and cold chambers; at the left-hand side, an assembly of measuring units; above the control panel, temperature control logometers.

The moisture resistance of the devices is checked by keeping them in a moisture chamber for several days.

The moisture chamber is rather a complicated device providing a prescribed temperature and humidity of the air. The prescribed temperature is provided by heaters while a definite humidity is ensured by evaporating water from a special humidifier. Uniform temperature is maintained due to circulation of the air within the testing volume provided by a fan, while uniform humidity is provided by circulation of the air through the water layer of the humidifier by means of another fan. The temperature is controlled and maintained by an electronic bridge and the humidity is maintained by an electronic psychrometer.

The electronic psychrometer is an indicating measuring-

and-recording instrument whose input is connected to an electronic bridge. Inserted into one of the arms of the bridge is a sensor the resistance of which depends on the relative humidity of a medium being checked.

At the end of the test for long-term action of moisture before removing the semiconductor devices from the cham-

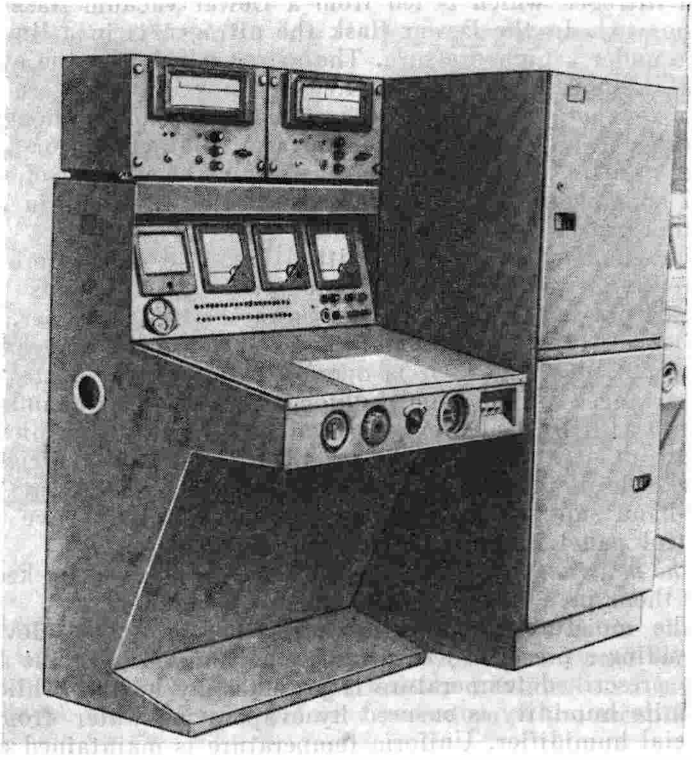


Fig. 112. General view of stand for thermal resistance tests

ber, a voltage stipulated in the type specifications is applied to them for 5 minutes.

After removing the devices from the chamber and keeping them under normal climatic conditions for 2 hours, they

are subjected to visual inspection and their electrical parameters are measured according to the measurement procedure of the acceptance tests.

The resistance to thermal cycling is checked as follows. The semiconductor devices are placed into a heat chamber the temperature in which is preliminarily raised to the rated temperature of the device case and are kept there for half an hour. Then the devices are immediately placed into a cold chamber whose temperature is preliminarily brought down to a required value and are kept there for half an hour. The time of transferring the device from chamber to chamber should not exceed 1 minute. After keeping the devices within the cold chamber for the specified time they are again transferred into the heat chamber, and the testing cycle is repeated. Usually three cycles are made.

After the tests the devices are kept under normal climatic conditions for at least 2 hours and then their main electrical parameters are measured according to the measurement procedure of the acceptance tests.

The resistance to reduced atmospheric pressure is checked in a pressure chamber at a pressure of 5 mm Hg. At this pressure the devices tested operate under specified operating conditions during a predetermined time period registered in the type specifications and then the parameters of the devices are measured according to the same specifications. After the tests the devices are withdrawn from the chamber and the main electrical parameters are measured.

The resistance to elevated atmospheric pressure is checked in a pressure chamber at a pressure of 3 atm gauge. The test is conducted during a given time without applying a voltage to the electrodes of the devices. After completing the test, measurements as in the preceding case, are performed.

The resistance to the action of sea fog is checked as follows. The devices are placed in a chamber at a temperature of 26°C, in which conditions of sea fog are produced by spraying a special synthetic solution of salts. The total testing time is equal to several days. After completing the test, the main electrical parameters are measured.

Some types of semiconductor devices are tested for resistance to fungi. These tests are conducted according to special instructions and fall beyond the scope of this book.

Each climatic test should be followed by visual inspection before proceeding to measure the electrical parameters of the tested semiconductor device. The devices are considered as having passed the test if they prove to be free of defects affecting their normal operation, have an appearance complying with general and type specifications, and their electrical parameters (or variations of these parameters) remain within the limits stipulated in the type specifications for the given test. Furthermore, during moisture resistance tests the devices with creeping discharges within the case or on the surface are rejected.

REVIEW QUESTIONS

8.1. How do surrounding conditions affect the operation of semiconductor devices?
8.2. How are tests of semiconductor devices classified?
8.3. What operations are carried out during the construction tests?
8.4. What is meant by electric and thermoelectric ageing of semiconductor devices?
8.5. Sketch the electric circuit diagram used for thermoelectric ageing of rectifier diodes.
8.6. To what kind of mechanical tests are semiconductor devices subjected?
8.7. To what kind of climatic tests are semiconductor devices subjected?
8.8. Name the equipment used for mechanical tests of semiconductor devices.
8.9. Name the equipment used for climatic tests of semiconductor devices.

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TO THE READER

Mir Publishers welcome your comments on the content, translation, and design of the book.

We would also be pleased to receive any suggestions you care to make about our future publications.

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